NUCLEAR ENGINEERING VOL. 4 NO. 37 APRIL, 1959

AEA RE-GROUPED

MAJOR reorganizational changes have been announced by the Atomic Energy Authority. The Authority will now comprise four groups instead of three, the previous Industrial Group having been divided into a Development and Engineering Group and a Production Group. The Authority's announcement states that, at the same time, the full-time technical Members will again assume executive responsibility for particular groups, in addition to their functional responsibilities and general duties as members of the Board.

Sir William Cook, with the title of Member for Development and Engineering, will be executive head of the Development and Engineering Group, and will in addition retain corresponding functional responsibilities throughout the Authority. Sir Leonard Owen will have the title of Member for Production (Designate) and will be executive head of the Production Group. Sir William Penney, whose appointment as Member for Scientific Research was announced a few weeks ago, will in addition become the executive head of the Research Group, while retaining his functional responsibility for scientific research throughout the Authority. The appointment of a Member for Weapons Research and Development has still to be announced.

The responsibilities of the new Engineering and Development Group are classified as development, design and construction of reactors and associated plant (with the exception of certain development work which will continue to be undertaken by the Research Group); engineering consultant work for the electricity authorities, overseas organizations and industry; general engineering design and construction of all major building projects. The Group will have headquarters staff at Risley and will control the Dounreay Experimental Reactor Establishment, the Culcheth Laboratories and the R. and D. organizations at Capenhurst, Windscale and Springfields.

The Production Group will be responsible for the operation of the Authority's factories including Calder Hall and Chapelcross and the research and development directly associated with the factory processes. It will also take over the commercial activities of the existing industrial power branch. The headquarters staff for the Group will remain at Risley.

In part the reorganizational changes fall directly in line with the recommendations made in the Fleck reports. It was felt with the existing organization, uncertainties were inevitable in the allocation of final responsibility for the running and organizing of plant that was predominantly experimental in character. The division also falls more into line with usual industrial practice where development and operation are considered as two quite separate functions. It is important to note that DFR and the AGR experiment at Windscale will come under the direct auspices of the Development and Engineering Group. This should ease considerably the planning of the experimental programme and should ensure that the reactors are operated in such a manner as to give the maximum information. On the other hand, the production reactors of Calder Hall and Chapelcross come firmly within the scope of the Operations Group, who will not be embarrassed by competitive demands for experimental facilities.

Contrary to the recommendations of the Fleck committee is the decision to ally the responsibilities of the Members of the Atomic Energy Authority with duties as executive heads of the various Groups. At one time it appeared that the Authority had accepted the Fleck recommendations when Sir John Cockcroft resigned from the directorship of Harwell. It should be noted, however, that, taking the Research Group as an example, Dr. Schonland remains as the director of AERE and Mr. Fry as the director of Winfrith (answering to Dr. Schonland). The dual responsibilities need not include detailed administration work nor need the Members be involved in day-to-day running of the establishments. The new arrangement can, in fact, allow them greater access to all establishments and greater power in organizing and co-ordinating the work of individual divisions. It has yet to be seen, however, whether the opposite will not result, particularly as regards research activities throughout the Authority, and that the valuable work of co-ordination, that Sir John Cockcroft started, will not be wasted.

Certainly the Industrial Group was becoming too large to be manageable and too diverse in its activities. It seems unfortunate, nevertheless, that these moves could not have been made twelve months ago as repeated upheavals in the Groups' organization are most unsettling to staff. Let us hope that we can now look forward to a long period of stability once final details have been settled.

CEGB Berkeley Laboratory

THE Central Electricity Generating Board is beginning to construct, on a site adjoining the Berkeley Power Station, a Research and Development Establishment, costing roughly £1 million. When complete, the laboratories will be staffed by 150 qualified people divided into three main groups, viz. metallurgy, physics and engineering. The laboratories will be fully equipped for handling radioactive materials, and the facilities will include three heavily shielded caves and a great number of shielded cells, so that fuel elements can be handled within a few weeks of extraction from a reactor.

The main work of the Establishment will concern the problems involved in the operation of the Board's reactors. It is not intended that the research should be competitive with that of the Atomic Energy Authority, but rather complementary. Taking as an example fuel elements, although there is bound to be a certain overlap of interests between the Board and the Authority, the Board is in the position of customer and the Authority (as one of its functions) is in the position of supplier. Theoretically as the AEA is also charged with the responsibility for leading nuclear developments, the aims of the two are the same, but the viewpoints are, nevertheless, different. The Generating Board is concerned with obtaining the maximum quantity of electricity from a given supply of fuel, whereas the AEA has a vested interest in increasing fuel sales.

The AEA has, of course, its own power station responsibilities at Calder Hall and Chapelcross and as consultant to the South of Scotland Electricity Board and possible overseas stations, but its direct experience will be confined to low temperature and experimental plant in which high burn-up is not required.

In addition to the metallurgical examination of fuel elements, a great deal of research is necessary on the detailed conditions obtaining in reactor fuel channels. A pressing requirement is the determination of maximum can temperatures in various parts of a reactor and at various stages of burn-up; these figures cannot be calculated with any precision. Their evaluation is critical in assessing the maximum permissible rating of the fuel and equating this with the fuel life to enable the ultimate cost of the generated electricity to be minimized.

On the engineering side, a great deal of proving research will be necessary. A nuclear power station contains many novel features, the integrity of which can only be demonstrated by careful study under operational conditions. Control systems alone provide an extensive field for operational research.

CEGB Largest Owner/Operator

It is clearly logical that such work should be carried out by the largest owner and operator of nuclear power stations—which the Generating Board will be by 1962; the rating of Hinkley Point alone will be greater than the sum total of the AEA's reactors. It is also logical that the purely observational research will be backed up by theoretical and practical development; confining the laboratories' activities to the mere taking of readings would lead to a sterile situation. It can be argued that multiplication of effort will be inevitable and that some identical research will be going forward within the AEA, within the Industrial Groups and at the Generating Board's laboratories. The interests of the AEA will, however, progressively move on to advanced reactor technology, whilst the Board (as the only body with immediate access to "developed" plant) gains steadily in experience of current types. During this process the Board can relieve manufacturers of a significant amount of development work, as, for example, in the heat transfer field, where an individual group may not be able to justify on economic grounds an expensive programme of research with only limited application. We can expect the Board to lead manufacturers in the design of particular components, rather than leave to manufacturers the onus of undertaking the full development themselves.

CEGB's Growing Experience

Concomitantly the growing expertise within the Generating Board will result in the Board taking a greater responsibility in the design of stations and this entry into the R. and D. arena can be taken as heralding the end of the turn-key contract system and the break-up of the rigidly bound consortia. By most people this was regarded, in any case, as an inevitable process of evolution. It does, however, throw into relief the problem that must soon be faced by the Groups and that is the ultimate future of their large development design and contract teams which, although highly effective forces in conducting overseas business, will be somewhat redundant on the internal market. There is still a place, of course, for the smaller nuclear design team, acting in a similar capacity to existing civil engineering consultant concerns, but unless the export market is much greater than is generally believed, it is difficult to see how five design organizations can be fully employed if Calder type reactor engineering is their sole concern.

There are two courses open. One is that some of these design groups are disbanded, but it is difficult to see how this can come about without a bitter and perhaps damaging struggle for survival. Alternatively, they can extend their activities into wider fields, so that they are able to undertake not only design consultancy work on other reactor systems (by, perhaps, association with overseas companies) but also on allied engineering projects requiring similar techniques such as are found in the chemical engineering industry. In either case independence of their present parent companies seems a desirable prerequisite, and an effective formula for continually gaining from the AEA experience of advanced types must be evolved.

DIGEST...

Surveying Significant News

Westinghouse-Rolls-Royce Agreement on Dreadnought Propulsion Unit Finalized

Negotiations between Rolls-Royce and Westinghouse Electric Corporation, which have been going on for nine months, over the purchase of a reactor propulsion system and the associated manufacturing know-how for Britain's first nuclear propelled ship, the submarine Dreadnought, have been finalized. A complete set of machinery, similar to that being installed in the Skipjack class of vessel will be obtained from Westinghouse and the Dreadnought hull design has been modified appropriately. The contract provides for the supply of fissile material from the United States until 1968 and Rolls-Royce will be given access to the necessary commercial information which would allow, for example, fuel element manufacture. It is understood that the AEA will not be given similar access as the know-how is regarded as being commercially secret. Work on the land-based prototype at Dounreay will continue.

Lord Plowden To Join British Aluminium

It is now confirmed that Lord Plowden will be relinquishing his post as chairman of the AEA at the end of his present term of office which expires on December 31. He leaves to become chairman of British Aluminium and vice-chairman of Tube Investments. His successor has not been named.

Contract for Japan's Calder Hall-Type Reactor Not Yet Finalized

Although the G.E.C., Simon-Carves Group has been selected for special contract negotiations by the Japanese, no Letter of Intent has yet been sent. The design submitted by the consortium included a number of changes from Hunterston; in addition to provisions for earthquake resistances, the system of bottom charging adopted for the S.S.E.B. station has been abandoned (because of civil engineering considerations) and a hollow fuel element has been proposed. Present discussions centre round detailed financial terms and sub-contract conditions.

Only One CEGB Nuclear Station Contract This Year

Tenders for a 500 MW station at Trawsfynydd are now being considered: a decision can be expected within the next four months. Four tenders were received—from the G.E.C., Simon-Carves Group, the A.E.I. John Thompson Group, The Nuclear Power Plant Co. and the fifth consortium Atomic Power Constructions. English Electric did not tender, presumably because they would prefer to concentrate on Dungeness, the next power station to be built in the Board's nuclear programme. The Minister of Power has yet to approve the Dungeness site, and, even then, the contract will not be awarded until next year. Following this the programme will be accelerated to allow a minimum installed capacity of 5,000 MW by 1966.

CEGB Seeks Additional Sites for Nuclear Stations—Sizewell Approved

East Suffolk County Council planning committee are recommending to the Council that the CEGB's proposal to construct a nuclear power station at Sizewell should be approved. The site chosen was regarded as "the least objectional" of those that had been suggested. CEGB proposes to investigate a number of areas on the coast of Anglesey to determine their suitability as sites for nuclear power stations. The site at Edern in Caernarvonshire which has already been nominated as suitable for development, is opposed by the Council for the Preservation of Rural Wales; it has been reported also that the Isle of Wight has been surveyed and that trial borings will be made at Hamstead on the Newtown river.

Fifth Nuclear Explosion in Plowshare Project Planned

In an address to the 1959 Forum on Natural Resources Conservation, ex-Commissioner Libby gave details of the Plowshare programme for nuclear devices which have been detonated underground so far. The first at Rainier was on September 19, 1957, and proved that radioactivity can be contained. Three further tests were made last October at Logan and Blanca. The fifth explosion is planned for Carlsbad, New Mexico, in salt deposits to test the possibility of storing energy in the form of heat for subsequent conversion to power.

First Reactor at Chapelcross Generates Power

First of the four reactors at Chapelcross fed power into the national grid on February 25. This reactor diverged last November and has now concluded its testing and commissioning period. Programme date for start-up was March 1. Construction of this station is under the control of Merz and McLellan acting as agents for the AEA's industrial group. This is the first occasion on which a commercial organization has been employed in this way on a major project. Chapelcross will be officially opened on May 2. The remaining three reactors are to be modified to allow the inclusion of graphite sleeves in the coolant channels to minimize Wigner growth.

AEA Reorganizes Isotope Marketing

Reorganization of the AEA isotope division's production and marketing of radioactive isotopes which has been handled in the past jointly by the Isotope Division at Harwell and the Radiochemical Centre, is to be vested entirely in the Amersham Group. The present Director of the RCC, Dr. W. B. Grove has been appointed director of the reorganized centre. Research will be continued at Harwell under a newly formed Isotope Research Division (answering to Dr. Spence), which will also continue to operate the Isotope School. The former head of the isotope division, Dr. Henry Seligman has been on detached duty from the Authority, acting as member of the IAEA for isotopes and research. It is likely that this appointment will be made permanent and Dr. Seligman will remain in Vienna. This transfer of responsibilities will thus close a not inglorious chapter in the history of Harwell.

Organic Moderated Study Initiated in Italy

CNRN—the Italian AEA—and Montecatini are to establish a group to undertake the development of the organic moderated and cooled reactor system. Montecatini was associated with Atomics International in the only organic moderated reactor included in the SENN tenders. The present agreement is in line with the policy of CNRN to set up collaborative groups to study various reactor systems so that development can proceed on a wide front.

Hold-ups in Construction on the Indian Point Station

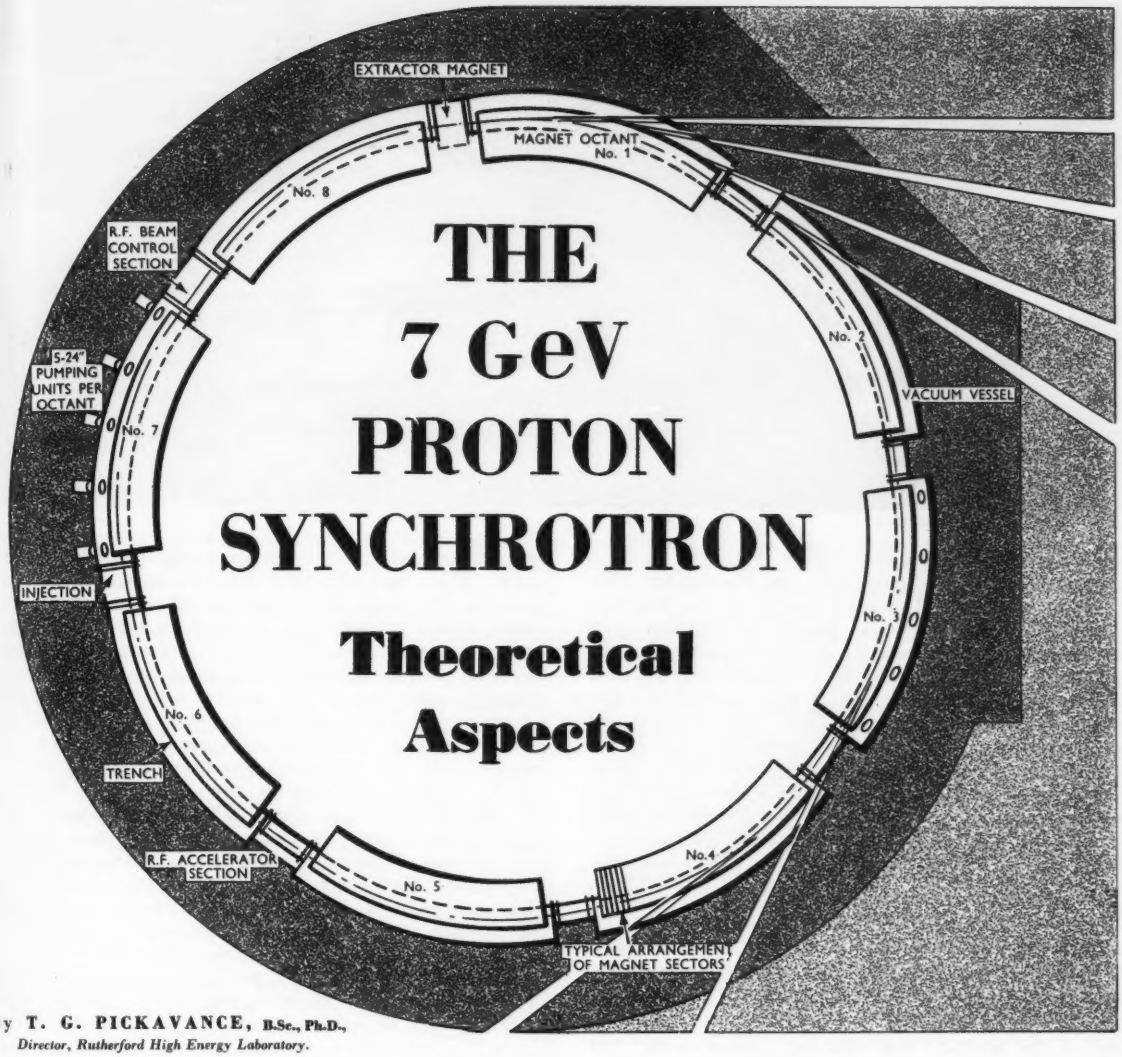
Completion of the oil superheat pressurized water nuclear power station at Indian Point, being constructed by Consolidated Edison, will be delayed nearly a year, due to technical difficulties. In addition, the final cost of the plant is now estimated to be in the region of $100 million, nearly double that originally estimated in 1955. In his testimony to the Joint Congressional Atomic Energy Committee, the senior Vice-president blamed the increased cost on rising prices of components, but also on the paucity of information that was available at the time the original estimate was made. Consolidated Edison, in company with other utility companies and manufacturers, is pressing the AEC to take a greater financial responsibility in the construction of full-scale power stations.

Gas-Cooled Heavy Water Moderated Pressure Tube Reactor Project

Contract has been signed between the U.S. AEC and the East Central Nuclear Group Inc., in conjunction with the Florida West Coast Nuclear Group, for research and development work on a gas-cooled heavy water moderated nuclear power plant. The plant will be constructed in the Florida West Coast area under the Commission's power demonstration reactor programme. The plant will be rated at 50 MW(E) and will be built on the pressure tube principle. Cost of the research programme, estimated at $18 million, will be shared equally by East Central Nuclear Group and the AEC. Maximum AEC assistance, including waiver of use charge for fuel and heavy water, is just over $13 million. Construction costs estimated at $26 million and excess operating costs (over conventional plants) estimated at about $5½ million over the first five years, will be borne by Florida West Coast Nuclear Group. The plant which is scheduled for completion in June, 1963, is to serve as a prototype for a 200 MW plant. GNEC has been nominated nuclear design agent.

Reactor Briefs

The Transient Reactor Test Facility (TREAT) at the National Reactor Testing Station, Idaho Falls, achieved criticality on February 23. . . . University of Wyoming's L-77 laboratory reactor, built by Atomics International, began operating on February 28. . . . West Berlin University's 50-100 kW water boiler reactor went critical on March 14.



THE 7 GeV PROTON SYNCHROTRON

Theoretical Aspects

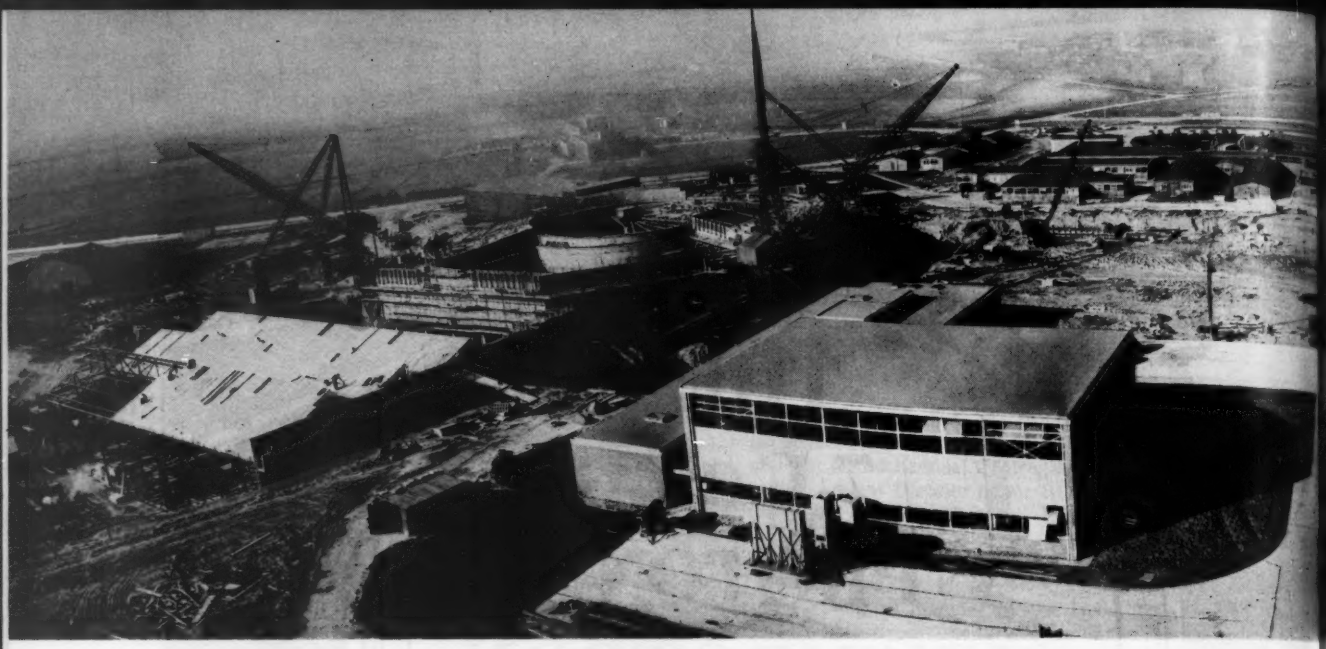
by **T. G. PICKAVANCE**, B.Sc., Ph.D.,
Director, Rutherford High Energy Laboratory.

THE Rutherford High Energy Laboratory is the first laboratory of the National Institute for Research in Nuclear Science, and will be used by scientists from the Universities, the Atomic Energy Authority, and other bodies, and by staff of the Institute who will also operate the research facilities. The main activity at present is the construction of the new 7 GeV proton synchrotron, which has been undertaken by the Atomic Energy Authority at the request of the Institute. The specifications were adopted by the Institute after discussion with the Universities and the accelerator specialists of the Authority.

The high energy particles produced by this machine will be used in fundamental studies of nuclear and sub-nuclear phenomena, a field in which no direct practical applications can as yet be foreseen. The justification for the great expense and the efforts of teams of highly qualified scientists and engineers is to be found in the fact that the unsolved problems in this field closely involve the most fundamental forces of nature. In these circumstances the question as to whether valuable practical application will be based directly on the results of the work need not normally be asked, but most advances in practical affairs have been made possible by inquiry of a kind in which the practical developments were neither sought nor foreseen, and this field may not be an exception. Moreover, there are certain to be other benefits. The most obvious one is a prime reason for initiating the project, namely the effect on the young scientists trained in the Universities when these modern facilities for research are used by the University departments. Others, perhaps no less valuable, are the advances in engineering and technology in the industrial firms which contribute to the construction, and the training of the young men who pass through the design and development teams during the course of the work. The range of practical problems encountered in a large accelerator project, and the subsequent nuclear research, is exceptionally broad.

Historical Background

The original motive for research with fast particles was to study nuclear structure. It was known 30 years ago that nearly the whole of the mass of matter is concentrated in the nuclei of atoms, and that the nuclei are extremely small in relation to the size of the atoms themselves. It was also known that the nuclei of certain heavy atoms undergo spontaneous transitions into other nuclei, with the emission of particles and electromagnetic radiation. Bombardment of nuclei with artificially accelerated



particles made possible a wider range of nuclear transmutations under controlled conditions, and the detailed study of nuclear structure. This work has led to the discovery of artificial radioactivity and nuclear fission, and to a mass of detailed knowledge of nuclear structure, but the fundamental problem of finding a complete and accurate understanding of the forces which bind together the particles in a nucleus remains unsolved. The strength and range of action of the forces are quite well known, but their detailed mechanism is not well understood. For some years the study of this problem has been following a fairly familiar pattern in scientific research; attempts to study certain details of a particular phenomenon have frequently resulted in the discovery of unforeseen effects and new phenomena, which then have to be studied in their own right.

New Particles

It has been believed for many years that the nuclear forces are characterized by the exchange of unstable particles (π- mesons or pions) between the protons and neutrons of the nucleus; the observed masses (about 280 electron masses), lifetimes (about 10^{-8} sec for the electrically charged varieties of the pion) and other properties of these particles can be broadly reconciled with the range and strength of the forces and many of the characteristics of nuclei.

Particles of such a short life as the pions, having merely a transitory existence inside nuclei, can only be observed directly by creating them artificially in nuclear collisions and the bombarding particles must be at least sufficiently energetic to create the pion "rest mass" of 280 electron masses (i.e., about 140 MeV). The binding energy of an individual neutron or proton inside a nucleus is only a few MeV, so that a much greater energy is needed to create a pion than to induce a simple nuclear transmutation. A principal reason for making more powerful accelerators than the early Cockcroft-Walton generators and cyclotrons, which had been used in the first experiments on nuclear structure, was therefore to attempt to create pions and then to study their interactions with other particles. Engineering and technology were sufficiently advanced for such machines to be built just after the war, but the machines are expensive and public recognition of the importance of large-scale scientific research was also an essential feature, in order to ensure the necessary public patronage. Pions were created, and can be produced by any efficient accelerator with an energy of 200 MeV or more. They were also (and earlier) observed to be produced by the much more energetic but much less intense cosmic radiation. However, at about the same time other, and more massive, unstable particles were seen to be produced by cosmic radiation. This was a spur to the accelerator builders, and, so far mainly with the help of the Cosmotron (3 GeV) and the Bevatron (6 GeV) in the U.S.A., quite an extensive catalogue of these particles together with their properties has been developed. They can be classified into groups now called heavy mesons (K- particles), of mass about 1000 electron masses, and hyperons which are somewhat more massive than protons and neutrons. They are believed to be closely concerned with nuclear forces, because they are readily produced in high energy nuclear collisions, and although short-lived, they live for a much longer time than could be understood according to the ideas current before their discovery.

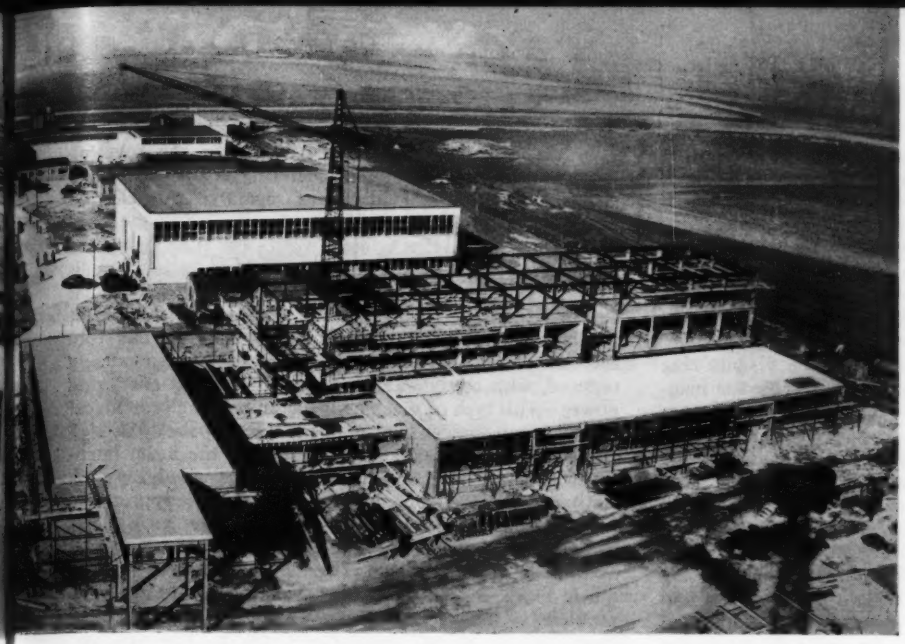
Certain other particles are produced, as decay products of unstable particles, which do not interact strongly with nuclei; an example is the μ- meson or muon, which lives for about 2 μ sec before decaying into an electron and is produced by the spontaneous decay of a pion.

Another class of particles, produced by the Bevatron, are the antinucleons (i.e., antiproton, antineutron) which are stable, but are annihilated in encounters with protons and neutrons; the proton or neutron is also annihilated, with the release of the energy originally expended in the creation of the antinucleon. The existence of antiparticles had been postulated on theoretical grounds before their discovery; the first antiparticle to be discovered, long ago, was the positron or positively charged electron.

The study of the modes of creation and the detailed properties of all these new particles, and the way in which they interact with other particles, is the main object of present-day high energy research, and will be the principal field of the Rutherford Laboratory. It should be mentioned in passing that the nuclear structure studies, at lower energies, are by no means complete and are still being pursued vigorously with modern equipment.

Choice of Machine

The minimum energy required for the production of the known particles of interest is about 6 GeV. This was a starting point when attempts were first made to choose a particular machine for national use. However, there are other factors which influence a choice. The yield of



Panoramic view of the accelerator site showing the progress of construction at the end of February, 1959. The synchrotron circle can be seen between the cranes on the left-hand page.

particles, per incident particle, increases with energy, but the accelerated beam intensity decreases with increasing energy. Accelerators may be designed to produce beams of electrons or protons, but not both, and therefore the relative merits of these particles have to be considered. Beam intensity is an important consideration and, as a field of research becomes more sophisticated, further progress needs higher intensity and more refined measuring techniques, partly to achieve greater precision and partly to study rarer processes. Versatility is important in any research tool. Large machines are costly, and the cost of a given type increases rapidly with both energy and intensity. Clearly the relationship with other existing and planned machines, at home and abroad, must be taken into account. It may not be possible to build a machine to beat all others, but it is certainly important not to be outclassed.

The choice of protons versus electrons is a difficult one. Protons are more effective in producing the mesons and other particles, because they are themselves closely connected with nuclear forces. On the other hand, electrons can usually be accelerated in greater numbers, which partially offsets their disadvantage, and can also be used in research into electromagnetic phenomena, which cannot be tackled with protons. On the whole, proton accelerators have been more productive in high energy research and, after careful consideration, a proton machine was chosen as the first major accelerator for the National Institute. If, and when, a second large accelerator is contemplated, an electron machine will be a strong contender, on grounds of diversity of research equipment.

Six GeV was taken as the minimum proton energy, but the upper limit was not simply a question of economics. Although all the particles known at present should be produced at about this energy, no accelerator has yet operated at full intensity above 6 GeV and we should expect that there will be other important phenomena which can only be investigated at higher energies. Higher energies can be obtained at comparable cost, but only by sacrificing intensity. A 25 GeV proton machine is being built by CERN in Geneva, and since the United Kingdom participates in the work of CERN, with eleven other European nations, this machine will be accessible to British physicists. Therefore the decision was made to work in the highest energy range through CERN and to construct a machine for more intense beams at a lower energy. The two machines will thus be complementary.

The specification finally adopted, after much discussion with physicists and accelerator specialists, was for a proton energy of 7 GeV, with a beam intensity greater than 10^{11} protons/sec. Naturally this had to take into account the possibilities of the various types of equipment. In principle, two main types of accelerator may be considered: a linear machine or a circular machine using a magnet. A proton linear accelerator for this energy would be over a mile in length and, in the present stage of technological and industrial development in respect of some of its major components, would involve several times the construction time and several times the capital cost of a comparable circular machine. Two comments on linear accelerators are apt at this stage. First, electron linear accelerators have as yet no rival for energies greater than 10 GeV or so, on account of fundamental difficulties in circular electron accelerators; the light electrons radiate energy as they circulate, to an extent which increases as the cube of the electron energy in comparable circular machines. At 7 GeV it is already difficult to make good this energy loss from the accelerating system; the problem does not exist in linear machines. Secondly, linear accelerators have important advantages, as research tools, over circular machines. These are: the particle beam emerges intact from the end, instead of having to be extracted from a magnet with inevitable loss of intensity; much higher beam intensities can be accelerated to high energy; the machine may readily be extended at any time. The National Institute will shortly have a 50 MeV proton linear accelerator which has been built by the AEA at Harwell; this will be a most useful tool for "medium energy" physics and may eventually be extended to somewhat higher energy.

However, for the high energy work a circular machine was an inevitable choice. The only circular machine for which the required intensity can be guaranteed using established techniques is a proton synchrotron.

Operating Principles

The protons circulate in a vacuum vessel between the poles of a ring-shaped magnet, in orbits of constant radius. On each circulation they are accelerated by the application of a relatively small alternating potential difference (a few kilovolts) from a radiofrequency generator. As the particle energy increases, the magnetic field strength has to be increased in order to confine the orbits to a constant radius within the ring. The magnet is therefore laminated like a transformer to reduce eddy current effects, and the current through the magnet windings has to grow during each pulse of the acceleration process and to decay back to zero between pulses. The acceleration process is complete, on each pulse, when the magnetic field has grown to the maximum economic value consistent with satisfactory operation (about 12,000 to 16,000 gauss in iron-cored magnets of normal design).

Similarly, the frequency of the alternating accelerating voltage must be increased during the acceleration process, in order to keep in step with the increasing frequency of rotation of the protons around the ring. This frequency tracking has to be done with great accuracy, if serious loss of particles from the beam is to be avoided. Departures of more than one part in a thousand from the proper values of frequency and rate of change of frequency would be inadmissible, in a practical case.

The protons have to be injected into the magnet ring from a subsidiary accelerator, since for example the magnetic field cannot be precisely zero on account of remanent field and stray field effects.

The protons have to travel long distances during the acceleration process (about 100,000 miles in a large machine), and they must therefore be kept in a narrow beam by focusing forces to prevent too many of them from straying away in the presence of the disturbances caused by unavoidable errors. This is achieved by causing the magnetic field intensity to vary with position on and near the paths of the protons, in a carefully controlled way. Magnetic forces can then be made to direct the protons towards their proper orbits. In the conventional or constant gradient synchrotron the magnetic field is made to decrease slightly with increasing radius, but to be uniform in azimuth. The focusing requirement may be expressed mathematically by stating that a parameter n, defined as

$$n = -\frac{r}{B}\frac{dB}{dr}$$

where r is the orbit radius and B is the magnetic field, must be kept within about 10% of the value selected, which is between 0 and 1. The actual value of n must be chosen after a careful study of the equations of motion of the particles for the particular accelerator design, and the condition just defined must be satisfied throughout the acceleration pulse and in all regions of the magnet gap occupied by the protons. If this is done, the particles will execute stable oscillations of position about an equilibrium orbit, and the remaining requirement is to make the gap between the magnet poles big enough to contain these oscillations. Great care must be taken with magnet design, and with quality control in manufacture, to realize these conditions in practice. It is customary to divide the magnet into a number of sections separated by field-free regions which are convenient for injection, acceleration and extraction equipment.

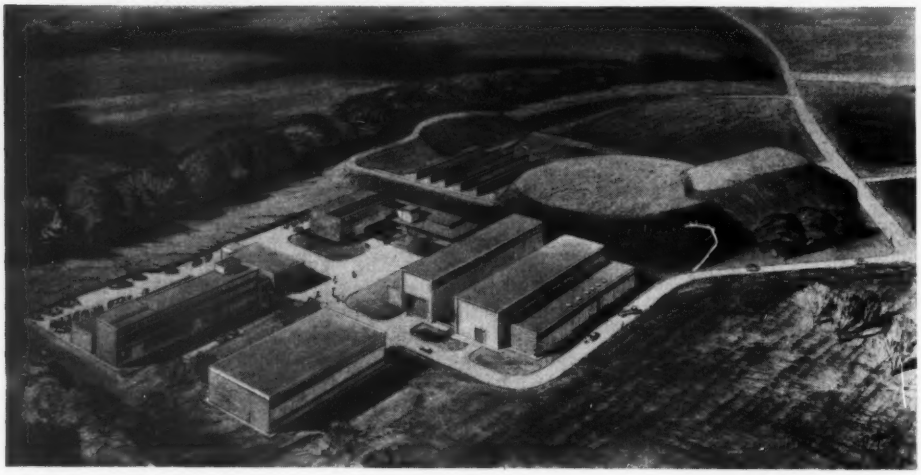
In the alternating gradient synchrotron the focusing method is modified. The magnet ring is divided into a large number of individual units separated by field-free regions, and a periodic variation of n is used in the units around the ring. If n is made very large (i.e. $\gg 1$), and alternatively positive and negative, then in certain conditions a strong focusing effect can be produced—much stronger than that which can be obtained in a constant gradient magnet. The oscillation amplitudes and therefore the size of the magnet gap can then be correspondingly reduced, with considerable savings in steel and energizing power. This type of machine is therefore more economical to build than the constant gradient type, especially at high energies, but its smaller aperture reduces the beam intensity which can be obtained under practical conditions. A constant gradient machine is therefore more appropriate for those energies at which its cost is not too great. The 25 GeV CERN machine is of the alternating gradient type; a constant gradient machine for 25 GeV would be very much more costly and would have almost insuperable problems of magnet design, consequent upon its very large size.

RUTHERFORD LABORATORY ACCELERATOR

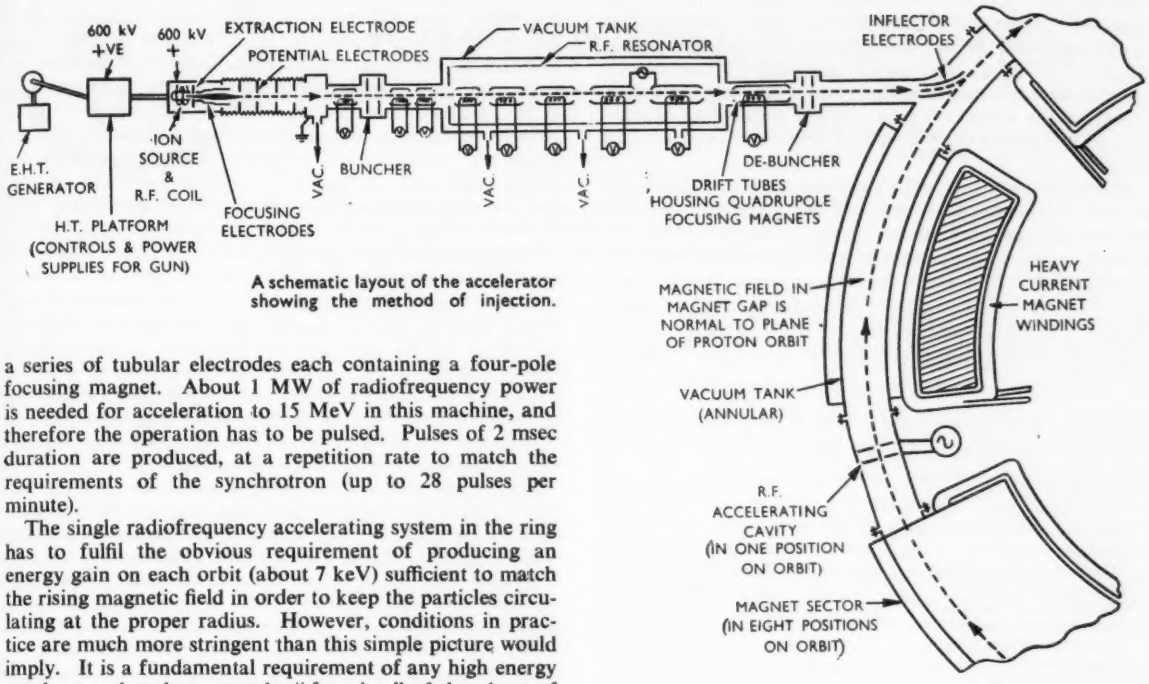
The new 7 GeV machine is a constant gradient proton synchrotron. The magnet ring is about 150 ft in diameter, and contains about 7,000 tons of special magnet steel mainly in ¼-in. plate. The useful dimensions of the magnet gap are 36 in. radially and 9½ in. vertically, and the maximum magnetic field, for the full energy of 7 GeV, is 14 kilogauss. The injector accelerator, from which a narrow jet of protons is guided into the magnet ring by electric fields between curved electrodes, is a 15 MeV proton linear accelerator. At the injection energy of 15 MeV the magnetic field is 300 gauss.

The injector consists of two main units, the ion gun and the linear accelerator proper. In the ion gun, protons are produced at low velocity in an ion source, which operates by maintaining an electrical discharge in hydrogen gas at low pressure. The protons are extracted from the ion source and focused into a beam, with the help of suitable electrodes to which high voltages are applied, and are then accelerated down an evacuated pipe, also with focusing electrodes, to an energy of 600 keV.

The 600 keV beam is admitted into the linear accelerator, which consists essentially of an evacuated copper cylinder excited in resonance by a 110 Mc/s radiofrequency source. The axial electric field generated by the radiofrequency system drives the protons along the axis, through



An artist's impression of the completed works. The mound covers the synchrotron and injector, the experimental area being on the left. Centre right are the buildings housing the motor alternator equipment with the control buildings alongside. In the foreground are laboratories and offices (left) and the magnet test and assembly buildings (right).



A schematic layout of the accelerator showing the method of injection.

a series of tubular electrodes each containing a four-pole focusing magnet. About 1 MW of radiofrequency power is needed for acceleration to 15 MeV in this machine, and therefore the operation has to be pulsed. Pulses of 2 msec duration are produced, at a repetition rate to match the requirements of the synchrotron (up to 28 pulses per minute).

The single radiofrequency accelerating system in the ring has to fulfil the obvious requirement of producing an energy gain on each orbit (about 7 keV) sufficient to match the rising magnetic field in order to keep the particles circulating at the proper radius. However, conditions in practice are much more stringent than this simple picture would imply. It is a fundamental requirement of any high energy accelerator that there must be "focusing" of the phase of the particles with respect to the RF field, as well as focusing of the direction of motion of the particles. In other words, if any disturbance should cause the particles to slip behind or run ahead of the alternating accelerating voltage as they rotate, there must be a positive influence at work which will correct the error. Disturbances are inevitable in practice; they are caused for example by departures from the correct frequency and noise in the electronics control circuits. With a million orbits in the acceleration cycle, any attempt to keep the particles in step by "dead reckoning" is bound to fail and the particles will not be accelerated. Fortunately, investigation of the equations of motion of the particles shows that this condition of phase stability can be achieved, but that very accurate matching of magnetic field and frequency and of the rates of change of these two quantities is required, particularly in the early stages of the acceleration. Since very great amounts of power are needed to energize the magnet (about 100 MVA peak), and the highly inductive magnet windings have a time constant of many seconds, it is chosen to make the radiofrequency variation follow the magnetic field variation, and not vice versa.

Probes are inserted in the magnet to deliver, through suitable electronic circuits, information to the master frequency generator of the RF system which determines the frequency of the accelerating voltage. The magnetic field cycle, on each pulse of operation, therefore determines the frequency law. Eventually a more refined system will be used, in which the motion of the particles themselves will transmit control information to the master frequency generator; this cannot be done initially because the intensity will be too small on first commissioning the machine.

Accelerator design is a struggle against the effects of errors and practical limitations in engineering. One aspect of this struggle is the phase stability problem. Another is the beam focusing problem already mentioned. However carefully the magnet steel is specified, however good quality control and "randomizing" of inevitable variations in magnet components is carried out in the factory, and however carefully the magnet units are aligned and installed (as summarized in the following article) it is certain that the machine will not operate unless further drastic measures are adopted. The stability of the particle beam is so delicately balanced that, with the utmost care and using the best known machining measurement and installation techniques, the remaining errors in the magnet will cause disastrous instability and loss of the beam. The additional measures to be taken are the following:

(1) Each of the 336 units which comprise the magnet yoke will be subjected to individual rigorous magnetic measurement on equipment which has had to be specially developed, and the resulting information programmed into an electronic computer which will then determine the optimum position in the ring for each unit.

(2) Correction windings between the magnet poles will have carefully determined currents passed into them, on the basis of accurate magnetic field surveys on the finished magnet, to reduce errors still further.

(3) Special electronics circuits will be devised to eliminate effects of ripple from the magnet power supply upon the particle motion.

Another problem is scattering of the protons by residual gas in the vacuum chamber. This causes the amplitudes of the particle oscillations to increase, and in a severe case virtually all the protons would be lost to the walls of the chamber. The magnet gap has to be kept to a minimum for reasons of economy, and also because of the practical limits imposed by the size of the magnet power plant. The scattering decreases with increasing energy, so that this is a factor in deciding the energy of injection. With the parameters chosen for the 7 GeV machine, successful operation demands a pressure not greater than 10^{-6} mm Hg. This is easily obtained in small vessels in the laboratory but in the special conditions of this large machine it is difficult.

Finally, there is the serious problem of radiation shielding. A beam of 10^{12} protons/sec at 7 GeV, such as may eventually be produced by the Rutherford Laboratory

machine, will produce very intense radiation in coming ultimately to rest. It is necessary to reduce the radiation in all occupied areas well below the agreed health tolerance values. The energetic radiation produced by high energy beams is very difficult to absorb, and it has been necessary to enclose the synchrotron in a shield with 6 feet of concrete and 20 feet of earth overhead, and much more around the sides.

Beams of particles, either protons extracted from the magnet by equipment which is still being designed or other particles sprayed from internal targets, have to be admitted through collimating channels in a 30-ft concrete wall into an experimental hall where the nuclear research equipment will be set up. The experimental apparatus will be complicated and heavy, and there has to be a profusion of cranes throughout the synchrotron area and the experimental hall.

Principal Parameters of the 7 GeV Proton Synchrotron

Maximum proton energy	7 GeV
Maximum magnetic field	14,000 gauss
Mean orbit radius	75 ft
Number of magnet sectors	8
Energy at injection	15 MeV
Magnetic field at injection	299 gauss
Magnet steel weight	7,000 tons
Magnet copper weight	250 tons
Magnet aperture, width	36 inches
Magnet aperture, height	9 inches
Pulse repetition rate	25-30 per min
Expected output	10^{12} protons/pulse
Acceleration system frequency	1.4 to 8.2 Mc/s
Number of accelerating units	1 (double)
Number of orbits during acceleration	10^6
Acceleration time	0.7 second
Total peak rating of motor-alternators (2) in magnet power supply	100 MVA approx.
Number of rectifiers in magnet power supply	96

Comparison with other Machines

The only other British machine in the GeV range is the 1 GeV proton synchrotron constructed some years ago at Birmingham University. In the United States there are two proton synchrotrons already operating, the 3 GeV Cosmotron at Brookhaven and the 6 GeV Bevatron at Berkeley. In the U.S.S.R. there is a very large 10 GeV machine at Dubna, with a 36,000 ton magnet. This has been operating for over a year, but so far at rather low intensity. With all these large accelerators a long period of careful development is needed, from first operation, to increase the intensity and the Russian machine will undoubtedly produce comparable intensity with the two American machines. It is hoped that the Rutherford Laboratory machine will produce a somewhat higher intensity, so that its energy disadvantage with respect to the Russian machine should not be a serious drawback. All these machines are of the conventional constant gradient type, and the Rutherford Laboratory machine differs only in that certain refinements have been incorporated as a result of the experience gained by the Americans and the Russians.

A slightly different type of "weak focusing" machine, using uniform field and obtaining focusing by non-perpendicular entry of particles into the edges of the magnet sectors, is being built at the Argonne National Laboratory in the U.S.A. This is planned for 12 GeV but its dimensions and other characteristics are not very different from the Rutherford Laboratory machine; its intensity will probably be somewhat lower. There are two smaller conventional proton synchrotrons, one for 2-3 GeV at Saclay in France, just completed, and one for a similar energy but higher intensity under construction at Princeton and Pennsylvania Universities in the U.S.A. A 10 GeV unit with an air cored magnet is being built in Australia.

Two 25 GeV alternating gradient proton machines are in an advanced state of construction; the one at CERN, already mentioned, and another at Brookhaven, U.S.A. These are "pioneering" machines. They will explore an energy region not yet tapped with accelerators, and no one can say what exciting phenomena may be discovered. In the Soviet Union a 50-60 GeV unit is being planned.

There are also many electron machines, which represent an alternative approach to high energy physics as mentioned already. The highest energy so far reached is just over 1 GeV in the U.S.A., but two electron synchrotrons for about 7 GeV are under construction in Cambridge, Mass., and Hamburg. The most exciting electron project, not yet started, is for a two-mile linear electron accelerator at Stanford University in California, for 40 GeV. This is a plan on the grand scale, requiring 1,000 high power microwave klystrons for the accelerating field.

Still bigger and more expensive machines are contemplated, based on new principles, but they are at the stage of laboratory models and complicated theoretical studies with computers. Some are still pipe dreams.

Against this background, the Rutherford Laboratory machine, as a high intensity source of important but little understood phenomena, should be a sound investment as a research tool for many years. We have tried hard to make the machine as adaptable as possible to the changing needs of research, and to profit from the experience of others who first built large machines. If the further development of high energy research throws up new requirements for very large machines, the Institute and the AEA should be able to provide them for use by the Universities. A programme of accelerator research is continuing in parallel with the construction of the 7 GeV machine.

Le Synchrotron de Protons 7 GeV.

En construction au Laboratoire de Haute Energie de Rutherford, situé aux côtés de l'Etablissement de Recherches d'Energie Atomique de Harwell, dont le personnel a fourni une grosse somme des efforts de conception, le synchrotron de protons 7 GeV représente l'activité principale de l'Institut National de Recherches en Sciences Nucléaires.

Dans le premier de ces articles, Dr. Pickavance retrace l'arrière-plan historique du projet, les raisons présidant au choix d'énergie et aussi le type de machine, et conclut par une description générale de l'Accélérateur du Laboratoire Rutherford et une comparaison avec les accélérateurs à haute énergie dans les autres parties du monde.

Le travail de la conception a été entrepris par Harwell. Dans le second article, Mr. Bowles donne, en détail, la conception des parties de mahines qui ont été finalement mis au point—certains éléments étant encore au stade de la planche à dessin—et discute les problèmes particuliers associés au maintien de la stabilité du faisceau et au maniement—d'une manière impulsée—des très grandes quantités d'énergie impliquées.

La construction de la machine entraîne un nombre de techniques de génie civil nouvelles et dans le troisième article de la série les principales caractéristiques sont décrites y compris la prévision de facilités expérimentales douées de souplesse.

Das 7 GeV Protonen Synchroton

Das im Rutherford Hochfrequenz Laboratorium, neben dem "Atomic Energy Research Establishment" in Harwell, im Bau befindliche 7 GeV Protonen Synchroton, an dem der Stab des "Establishments" mitgearbeitet hat, ist z. Zt. die Hauptarbeit des "National Institute for Research in the Nuclear Science" (Nationales Forschunginstitut für die Atomwissenschaft).

Im ersten Artikel behandelt Dr. Pickavance die historische Entwicklung des Projektes, die Gründe für die Wahl der Energie und ferner des Maschinentyps, und gibt am Schluss eine allgemeine Beschreibung des Accelerators im Rutherford Laboratorium und vergleicht ihn mit anderen Acceleratoren hoher Energie in anderen Teilen der Welt.

7 GeV PS

Engineering Design

By P. BOWLES, M.Sc., M.I.Mech.E., M.I.E.E.
(Project Engineer, A.E.R.E., Harwell)

The overall design of the proton synchrotron is now well established while the design of some details continues. Safety has been a dominant consideration followed by performance and reliability; these last are frequently antagonistic and require compromise solutions.

FROM the engineer's point of view, the proton synchrotron comprises six main installations: the injector which must accelerate protons to 15 MeV, this being the energy required to ensure that the protons will rotate in an orbit of the required radius with the field conditions at injection; the magnet which must provide the field of the required strength and spatial distribution; the radio frequency accelerator which must accelerate the beam so as to maintain it in the centre of the vacuum chamber as the magnet field increases; the vacuum system; the pulsed power supply and the control system. After injection the protons will revolve about a million times in their orbit before being extracted from the machine or being brought to bear on an internal target; thereafter the secondary radiation produced is absorbed in shielding. Fig. 1 shows a model of the plant.

INJECTOR

The injector is a 15 MeV proton linear accelerator, a diagrammatic layout of which is shown on page 155. The equipment for accelerating the protons initially comprises a direct current proton gun which is fed from a 600 kV revolving drum electrostatic generator. The direct current gun incorporates a pulsed radio frequency ion source, with its power unit, oscillator, and controls mounted on a high tension platform maintained at the electrostatic generator potential. Because of the large difference of potential between the platform and earth, mechanical drives are insulated, and all switching uses compressed air links.

The design of the linear accelerator beyond the source, shown in Fig. 2, comprises a radio frequency liner and drift tube assembly supported in a vacuum vessel 46 ft in length and 8 ft in diameter. The vessel will be exhausted to a pressure of 10^{-6} mm Hg by four liquid-cooled mercury diffusion pumps, each of 2,000 l/sec capacity. The vessel will be heavily ribbed to withstand atmospheric pressure and weighs 26 tons. To provide adjustment of the beam height the vessel will be mounted on four adjustable outrigger supports.

Removal of the D shaped cover will enable easy inspection of liner and its controls. The liner, a large resonant cavity which will be tuned to 115 Mc/s is 44 ft long and 5½ ft in diameter. It will have an array of 48 drift tubes of increasing length and spacing mounted along its axis. To produce the necessary radio frequency electric field between the drift tubes, large RF currents have to circulate on the surface of the liner and drift tubes supports, which calls for a high standard of surface finish. The liner, provided with pumping slots, will be fabricated from high conductivity copper, only 1/8 in. thick but will be reinforced by non-magnetic stainless steel rings and longerons to support the liner weight and that of the drift tubes. Thermal stresses will be minimized by the design of the supporting feet. At certain places along the length of the liner it will be necessary to make periodic adjustments to the electrical constants of the resonant circuit. This will be done by deflecting part of the surface which has been designed sufficiently flexible in a radial direction. Access will be gained to the interior of the liner through end hatches, the covers of which have garter springs between the joint faces to ensure a good RF joint.

Each drift tube assembly will comprise basically a four pole focusing magnet enclosed in an evacuated copper shell. The focusing magnet winding will be water cooled as heat dissipation in vacuum is difficult. The drift tube assemblies will be supported from the liner by two limbs at right angles, which are designed to permit adjustment in all directions to within 0.001 in. to obtain symmetry with the beam, and the correct position relative to the liner. Although similar in design, the 48 assemblies are different in dimension, the lengths varying from 3 in. to 13 in. and the bore from 0.8 to 2.0 in.

Cooling of the drift tubes and liner will be effected by circulating distilled water through tubes which will be soft soldered to non-working faces of the drift tubes and liner. In the latter case the temperature will be maintained at all parts of the liner to within ± 3°C by the water circulating contraflow in alternate tubes. This precise temperature control is necessary to prevent changes in dimension affecting the resonant frequency of the liner.

Die Entwurfsarbeit ist von Harwell durchgeführt worden. Mr. Bowles bringt im zweiten Artikel genauere Angaben über solche Teile der Maschine, die bereits endgültig festgelegt sind—einige Teile sind noch im ersten Reissbrett Stadium—und diskutiert die besonderen Probleme, die mit dem Aufrechterhalten der Stabilität des Strahles und mit der Beherrschung der sehr grossen Kräfte, die stossweise auftreten, verbunden sind.

Für den Bau der Maschine mussten eine Reihe neuer bautechnischer Verfahren entwickelt werden, und der dritte Artikel beschreibt die Hauptmerkmale dieser Verfahren mit Einschluss der vielfach vorgesehenen Möglichkeiten experimentelle Untersuchungen durchzuführen.

Sincrotono de Protones 7 GeV.

Bajo construcción en el Laboratorio de Alta Energía Rutherford en Harwell, cuyo personal ha provisto grande del esfuerzo relacionado con diseño, el sincrotono de protones 7 GeV representa la mayor actividad del Instituto Nacional de Investigación en Ciencias Nucleares.

En el primero, el Dr. Pickavance bosqueja el fondo histórico del proyecto, las razones que respaldan la selección de energía y también el tipo de máquina, y concluye con una descripción general del acelerador del Laboratorio Rutherford y una comparación con los aceleradores de alta energía en otras partes del mundo.

La labor de diseñar ha sido emprendida por Harwell. En el segundo artículo, el Sr. Bowles da, en detalle, el diseño de aquellas partes de la máquina que han sido finalizadas—ciertos componentes todavía están en la fase del tablero de dibujo solamente—y discute los problemas específicos asociados con el mantenimiento de estabilidad de haz y en manejar de una manera pulsada, las muy grandes cantidades de fuerza comprometidas.

La construcción de la máquina envuelve cierto número de técnicas novísimas de ingeniería civil, y en el tercer artículo de la serie, se describen las características principales, incluyendo la provisión de facilidades experimentales versátiles.

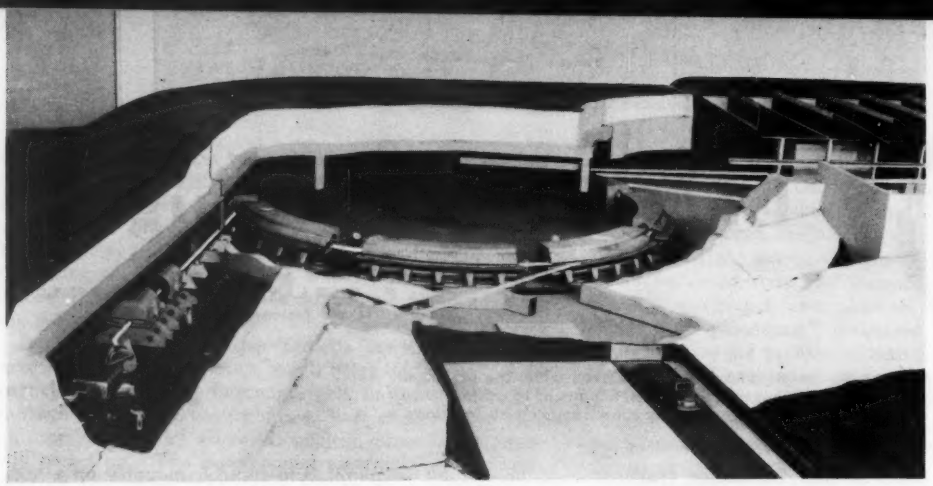


Fig. 1.—Sectioned model showing general arrangement of the plant and buildings. The path of the proton beam is indicated by the white line.

The RF power from a valve source will enter via a feed line through the base of the vessel and will be connected to the mid point of the liner. Similarly the base will be used for supporting the pumps and as a bulkhead for services.

THE MAGNET

The main factors affecting the design of the magnet for the proton synchrotron are the proton energy to be achieved, the mean radius of the orbit, the maximum values of the required flux density, and the air gap. Several secondary factors may affect the choice of magnetic circuit and other details of design, not the least important being access to the vacuum chamber, the shape of the required flux pulse, and the cost of steel.

For this machine a C shaped magnet was selected, with an orbital radius of 77.5 ft, a designed flux density (for 7 GeV) of approximately 14 kilogauss, and a magnet gap of 9 in. extending 45 in. radially. To establish 14,000 gauss in the gap, some 350,000 ampere-turns will be required and the stored energy in the magnet field will be of the order of 40 megajoules. The magnet is designed in eight units or octants separated by straight field free spaces which will accommodate the RF accelerating cavity, the injection equipment, the beam extraction equipment, targets and other experimental equipment. Each octant comprises 42 sectors, the whole 336 sectors weighing 7,000 tons.

Magnet Steel

In choosing steel for the magnet it is essential to give the correct relative weighting to the magnetic properties, viz. cost of the steel, cost of the power plant, and the recurring cost of the losses in the iron and copper. An exact judgment of the correct steel is most difficult, but final choice fell on a low silicon electrical quality steel, with the analysis given in Table 1.

TABLE 1.—Composition of Magnet Steel

Element	Min. conc.:%	Max. conc.:%
Carbon	0·04	0·06
Manganese		0·40
Phosphorus		0·03
Silicon	0·80	1·00
Sulphur		0·04

After annealing to obtain the optimum magnetic properties the steel has an ultimate tensile stress not less than 18 tons/in^2. Each magnet sector is built up of 1/8 in., 1/4 in. and 1/2 in. hot rolled steel plates, the greatest attention being paid to minimizing the crowning effect of the rolls. As sheets 11 ft by 10 ft were not available, two sheets of approximately half this size are welded together to form a sheet of adequate size. The general shape of the magnet is illustrated in Fig. 6, and the following manufacturing process illustrates the care taken to achieve high

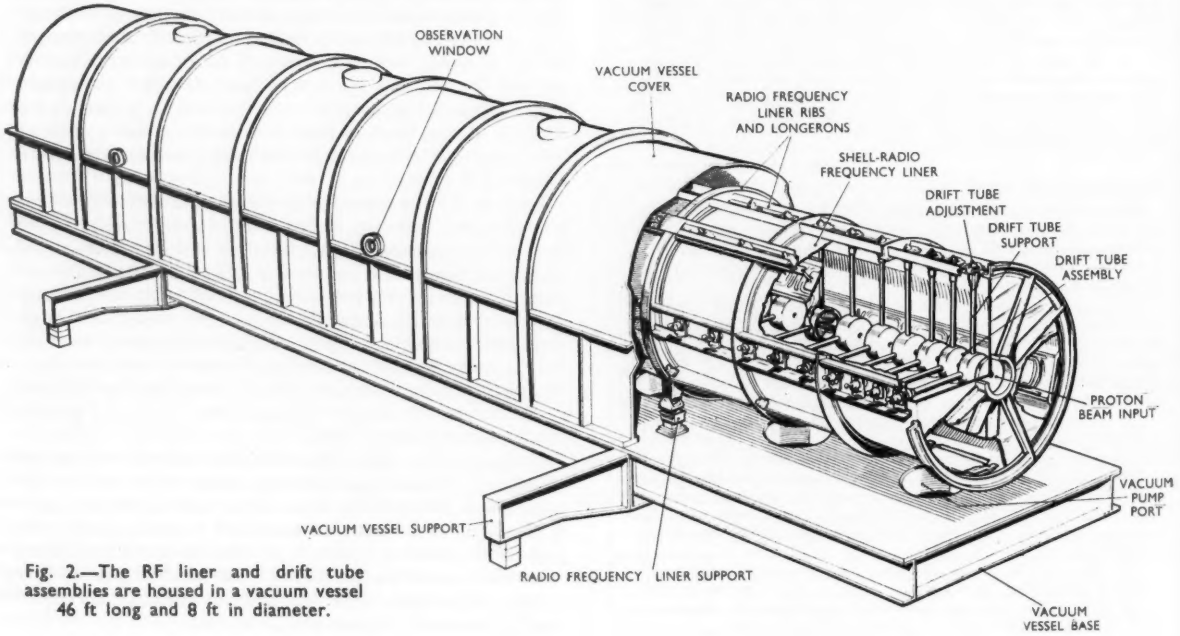


Fig. 2.—The RF liner and drift tube assemblies are housed in a vacuum vessel 46 ft long and 8 ft in diameter.

dimensional standards and magnetic uniformity of the 336 sectors.

The two plates forming one larger plate are matched to ensure that each piece not only comes from the same cast but from the same relative position in the ingot. Next each half plate is prepared for welding and a rough profile of the throat is cut by torch. The two sheets are then welded by a fusion process using CO_2 protection. The stacks of plates so produced pass to an annealing process and to final assembly via randomizing beds, where by particular selection it is ensured that the steel for each magnet is a random sample of the steel available at that time. About 75 tons of steel per batch is annealed in an inert atmosphere by a process cycle which takes about one month. The steel sheet so treated has optimum magnetic properties and skilful technology has produced flat plates.

After setting up a full sector, all the laminations are jig drilled at one setting, and taken apart for descaling and deburring. One side of each lamination is sprayed with an insulating coating, and after drying the laminations are assembled into a sector, each lamination being further insulated from its neighbour by phenolic paper. Specially hard resin sheet is inserted around the throat, this process being necessary to ensure clean machining of the edges, to prevent short circuiting of the laminations. After clamping the laminations with a uniform load of 50 tons, the side straps and back plates are welded in position to prevent distortion, and after tightening the lateral tie bolts the 50 tons load is removed. The welds will not introduce great circulating currents during operation of the magnet as the straps will not be linked by any appreciable flux. The sector weighing approximately 20 tons is next mounted vertically on the milling machine and in two operations the throat is machined to the final dimension. Upon delivery to site the sectors are checked dimensionally and the critical magnetic qualities measured in a rig; afterwards the magnet sectors will be erected on the magnet ring in specific positions determined by their quality. Forty-two sectors adjacent to each other form an octant which will be spanned by two symmetrically spaced magnetizing coils, as shown in Fig. 6.

The final design of the pole pieces has not yet been concluded but it is established that each one will comprise a stack of about 400 thin steel laminations of very accurate profile. The alternate laminations will be of different thickness and material, and will be bonded together to resist the severe disruptive forces. The laminations will be electrically insulated from each other and no bolting is permissible. It will be necessary to produce the pole in pieces in matched pairs to preserve magnetic symmetry.

Magnet Winding

In a highly inductive circuit of low resistance the number of turns required for a given current and a given rate of change, is dependent upon the applied voltage. In the case of the synchrotron described the coils have 42 turns and the applied voltage will be approximately 14 kV. The coils sides are being formed into the required radius from 50-ft lengths of extruded copper of section 1.375 in. × 2.625 in. The front conductors which are carried on the lips of the sectors will be connected to those conductors in the throat, by means of separately shaped end connections of the same section. The conductors will be cooled by demineralized water which is pumped through the 0.2 sq. in. hole in the centre. In this way the 3 MW of heat is dissipated, and scale deposits are avoided. The weight of copper in the coils will be approximately 350 tons.

The peak current for a standard pulse is 9,150 amp but under special conditions it is planned to increase this appreciably. The normal pulse rate will be 28 pulses/min and as the force on the coils is of the order of several tons per foot run the mechanical integrity of the coil and its clamps becomes a very difficult engineering problem.

The normal working voltage will be 4 kV d.c. to earth and 100 V between turns. This presents no difficulty but the problem of selecting an insulation to withstand the destructive mechanical forces is not so easy. It is proposed to use an insulation with some resilience as the continued application of the above forces could cause cracking of a hard material. On the other hand continued plastic flow could cause slackening of the clamps and loosening of the coils. The insulation chosen is turbobar insulation which is basically a mica silk tape, compounded with bitumen varnish. This insulation will bear extreme pressure without breaking down. After applying the tape to each formed bar, it is vacuum dried. Seven such conductors are then assembled so as to prevent voids, and the whole is bound together with tape. The pack is then pressed to size and the mica tape belt applied; the outer surface is finished with terylene tape, which is brushed with graphite compound to produce a low friction surface and so minimize abrasion of the insulation.

Under normal operating conditions the changes in temperature of the copper conductor could produce appreciable expansion or severe temperature stresses and an attempt has been made to minimize this by designing the system so that the temperature of the circulating water will be controlled to limit copper temperature variations to $\pm 4°C$.

In concluding the brief picture of the magnet it should be appreciated that it is necessary to maintain the plane of rotation of the beam in the main vacuum chamber correct relative to the injection and experimental apparatus. This accuracy can be affected by sinking or tilting of the foundation monolith, or distortion of the monolith during curing. In addition it is necessary to locate to extreme accuracy not only the angular and radial position of each sector, but

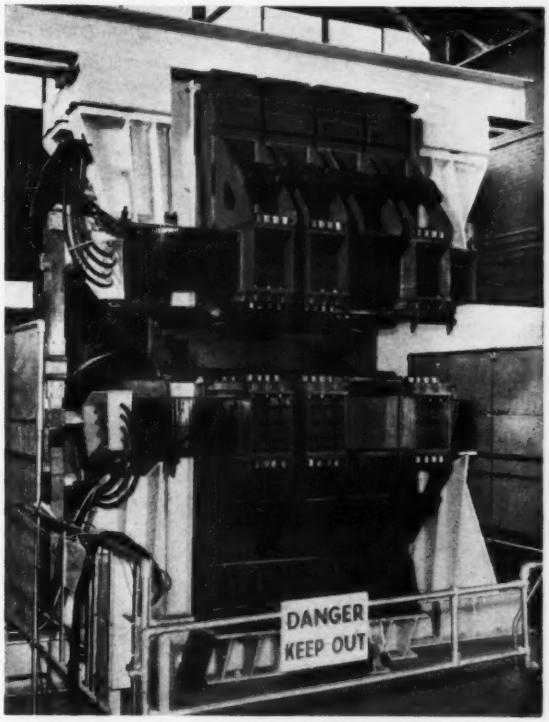


Fig. 3.—Each magnet assembly is fully tested on a rig similar to that shown above.

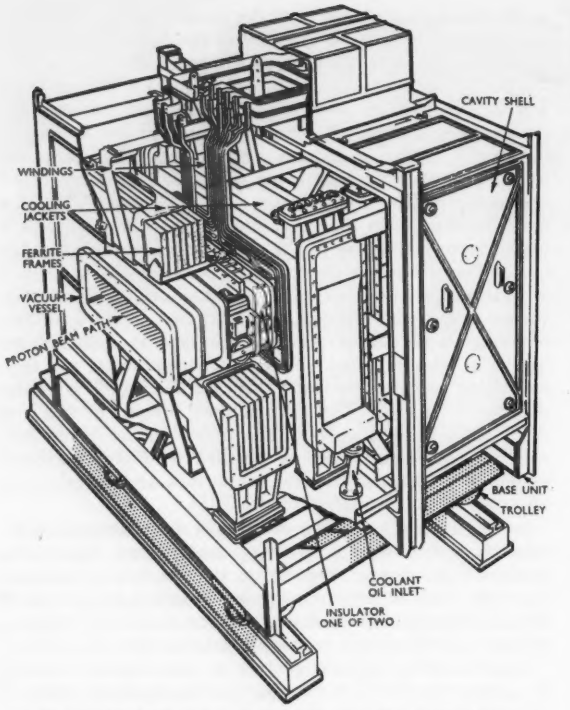


Fig. 4.—The RF cavity which accelerates the proton beam.

the height and tilt of each one relative to any other. The problem is doubly complicated since the erection has to be carried out to a scheduled programme and a bare minimum of time is available for the curing and drying of the concrete monolith. Furthermore once the magnet is set up and the coil and vacuum are installed no realignment of the magnets is contemplated unless there is a significant loss of beam current.

THE RF ACCELERATOR UNIT

Approximately every two seconds the proton linear accelerator will inject a proton beam tangentially into the main vacuum chamber and under the influence of the magnet the beam will be deflected along a circular path. At injection the protons will have a velocity of about 18% that of light and if the machine performs as designed the protons extracted for experiment will be travelling at 99% of the speed of light. A fresh beam will be injected every two seconds, and the accelerating period is 0.7 sec, during which time the protons go round the orbit about a million times. The accelerating device is known collectively as the radio frequency system, and comprises a primary frequency generator, a bias supply, a beam control unit and an accelerator unit. The last-named component produces the acceleration by means of a radio-frequency electric field.

The accelerator unit is fundamentally part of the main vacuum system, the flanges of the vacuum vessel located within the RF unit actually acting as electrodes for beam acceleration purposes. The insulators between the electrode flanges form a special design problem, as the choice of material is limited by radio-frequency loss characteristics; epoxy resin, porcelain and glass are all being tested. The bolts clamping the insulators must similarly be of low loss material.

The cavity, illustrated in Fig. 4 will be excited by a variable frequency oscillator whose frequency must vary from 1.4 to 8 Mc/s between beam injection and extraction. The peak voltage across each insulator will rise to 7 kV. The frequency control of the cavity is obtained by magnetically biasing the ferrite cores by a direct current, which changes the incremental inductance of the circuit. These cores are of picture frame type and are produced by bonding sintered blocks with an epoxy resin cement. Some 12,000 lb of ferrite will be used.

The bias winding requires 6,000 ampere turns. Initially a 600 amp, 10 turn arrangement will be used as this, on the basis of present knowledge, simplifies the control circuit, but it is anticipated that later a single turn 6,000 amp bias circuit will be used. The design permits conversion by simple reconnection.

In order to maintain the ferrite at 25°C working temperature oil cooling has been selected and some 45 kW will be removed under test conditions. The chilling of the oil will be effected by a Freon 12 refrigerator which has water cooled condensers. An oil dumping system is provided as a safety precaution.

VACUUM SYSTEM

Not only must the vacuum chamber be capable of being evacuated to a pressure of better than 10^{-5} mm Hg but the shell of the chamber must occupy a very minimum of gap length, be non-magnetic and circulating currents in its skin must not produce field distortion. It is equally necessary if non-metallic materials be used that there should be no accumulation of electrostatic charge on the surface, the material should have long life, and possess maximum resistance to any degrading effects produced by beam irradiation. Whilst satisfying these conditions the chamber should need a minimum external anchorage to prevent collapse, should be easily installed, and the inside should be freely accessible for experimental apparatus.

The vacuum chamber will comprise eight curved sections which correspond to the magnet octants and eight straight sections in the field free regions. The straight sections will be connected to the vacuum chamber by expansion bellows, and large vacuum valves will enable the chamber to be sectionalized to minimize pump down time after installing experimental apparatus.

Many designs of vacuum chambers can be evolved, and selected lines of approach depend upon opinion, cost, but more often upon decisions which may have been already taken for other components of the machine. The main contestants for the present machine were:—

(1) A partially self supporting chamber of insulating material.

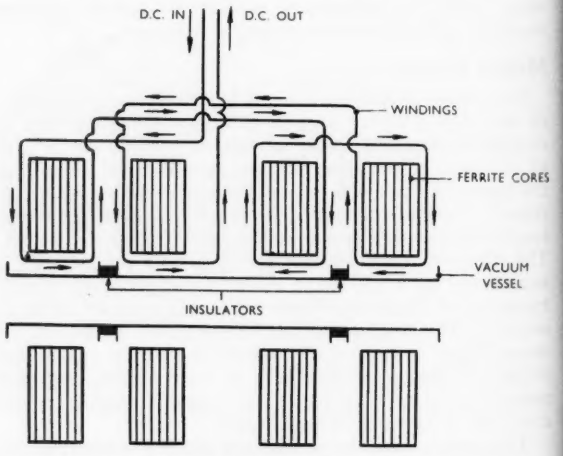


Fig. 5.—Bias winding of the ferrite cores, used for frequency control.

Nuclear

REFERENCE SHEET No. 1

SYNCHR

Table I. **Proton**

Current No.	Energy GeV	Location	Designation	Institution	Status	Cost	Focusing type	Orbit radius	Mean radius	Sectors No.	Field ma k-ga
	1	2	3	4	5	6	7	8	9	10	11
1	50	Leningrad, U.S.S.R.	50 GeV Synchro-phasotron	Research Institute for Electro Physical Equipment	Completion date 1961	—	strong, a-g	167 m	—	120	12
2	30	Long Island, U.S.A.	Brookhaven Alternating Gradient Synchrotron	Brookhaven National Laboratory	Completion date 1960	$29,000,000	strong, a-g	421·45 ft.	Magnet radius 280 ft.	240	13
3	25–28	Geneva, Switzerland	CERN 25-GeV Proton Synchrotron	European Organisation for Nuclear Research (CERN)	Completion date 1960	Sw.Fr. 100,000,000	strong a-g	70·08 m	100 m	100	12–
4	10·6	Canberra, Australia	ANU 10-GeV Proton Synchrotron	Australian National University	Design study 1953	—	weak, c-g	4·8 m	6·4 m	4	8(
5	12·5	Lamont, U.S.A.	ZGS (Zero Gradient Synchrotron)	Argonne National Laboratory	Completion date 1962	—	edge	71 ft.	87 ft.	8	21
6	12	Oak Ridge, U.S.A.	Southern Regional Accelerator	Oak Ridge National Laboratory	Model tests began 1957	—	strong, a-g	142 ft.	213 ft.	32	1(
7	10·6	Canberra, Australia	ANU 10-GeV Proton Synchrotron	Australian National University	Design study 1953	—	weak, c-g	4·8 m	6·4 m	4	8(
8	10	Dubna, U.S.S.R.	10-GeV Synchro-phasotron	Joint Nuclear Research Institute—High	Completion date 1957	—	weak, c-g	28 m	30·5 m	48	13
9	7	Harwell, England	7-GeV Proton Synchrotron	Rutherford High Energy Laboratory	Completion date Dec. 1961	—	weak, c-g	18·78 m	23·63 m	8	14
10	7	Moscow, U.S.S.R.	7-GeV Synchro-phasotron (Model for 50-GeV)	Thermotechnical Institute	Completion date 1959 (?)	—	strong, a-g	40 m	—	98c and 12x	9·
11	6·2	Berkeley, U.S.A.	Bevatron	University of California Radiation Laboratory	Completion date Feb. 1954	$9,700,000	weak, c-g	50 ft.	63 ft.	144	1(
12	$\geq$2·5	Aif-sur-Yvette, France	Synchrotron à protons "SATURNE"	Commissariat à l'Energie Atomique	Completion date Aug. 1958	6,000,000,000 francs	weak, c-g	8·42 m	~11 m	4, and 284 blocks	15
13	3·0	Upton, U.S.A.	Cosmotron	Brookhaven National Laboratory	Completion date 1952	$7,000,000	weak, c-g	30 ft.	30 ft.	4	13
14	3·0	Princeton, U.S.A.	3-BeV High Intensity Proton Synchrotron	Princeton University and University of Pennsylvania	Completion date Jan. 1960	$9,000,000	weak, c-g	30 m	40 m	16	13
15	1	Delft, Netherlands	Delfc Proton Synchrotron	Technical University Accelerator Division	Completion date Jan. 1959	—	edge	3·25 m	—	4	17·
16	1	Birmingham, England	The Birmingham Proton Synchrotron	University of Birmingham	Completion date July 1953	—	weak, c-g	5 m	16·5 ft.	—	—
17	200 (650) MeV	Leningrad, U.S.S.R.	Model Synchro-phasotron (Model for 7-GeV)	Research Institute of Electro-Physical Instruments	Completion date 1958	—	strong, a-g	5 m	—	34	5 (

luclear Engineering

PARTICLE ACCELERATORS*

YNCHROTRONS

. Proton Synchrotrons

ctors No.	Field max k-gauss	Power Input kW	Weight of Iron tons	Storage system	Rise Time sec	Weight of Copper tons	Aperture Width	Aperture Height	Pulse Rate	Output part./ pulse	Injector System Type	Input to RF kW	Frequency Mc/s	Shielding
10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
20	12	100,000	22,000	flywheels	3·8	—	20 cm	12 cm	6 per min	—	linac	—	2·6–6·1	—
240	13	—	4,000	—	1	400	6 in.	2⅜ in.	3 per min	—	linac	—	1·5–4·5	earth and concrete
100	12–14	27–32,000	3,400	flywheel	1	Al 130	14 cm	7 cm	1 per 3·5 sec	5×10^{9}	linac	16×6	3–10	baryte concrete 5·5 m
4	80	500,000	0	homopolar generator	0·7	80	22 cm	22 cm	1 per 10 min	—	cyclotron	60	1–7·5	—
8	21·5	~100,000	4,000	flywheel	1	65	32 in.	5½ in.	1 per 4 sec	$\sim10^{12}$	linac	80–100	4·2–14	earth 20 ft. above 100 ft. sides
32	10	700	1,200	condenser-choke	1/120	180	13 cm	6 cm	60 per sec	20 μa	AVF fixed frequency cyclotron	~1000	98–115	Vacuum chamber oval, 2·5×6·5 in.
4	80	500,000	0	homopolar generator	0·7	80	22 cm	22 cm	1 per 10 min	—	cyclotron	60	1–7·5	—
48	13	140,000	35,000	flywheels	3·3	2,700	150 cm	40 cm	5 per min	10^{9}–10^{10}	linac	—	0·19–1·45	—
8	14	100,000 kVA	7,000	flywheels	0·7	250	36 in.	9 in.	25–30 per min	10^{13}	linac	80	1·4–8·02	concrete and earth
c and 12x	9·5	—	2,700	—	1·5	—	11 cm	8 cm	12 per min	—	linac	500	0·65–8·5	—
144	16	100,000	9,700	flywheel	1·85	347	112 cm 44 in.	25 cm 10 in.	11 per min	—	linac	25	0·36–2·46	concrete 5–10 ft.
nd 284 locks	15	24,000 kVA	1,080	flywheel	0·8	55	between pole tips 52·75 cm	between pole pieces 17·54 cm	duration 3·2 sec	10^{10}	electrostatic generator	15	0·78–8·41	concrete
4	13·8	26,000	2,000	40-ton flywheel	1·0	70	28 in.	6 in.	12 per min	10^{10}–10^{11}	Van de Graaff	50	0·33–4·18	concrete
16	13·8	3,000	400	capacitors choke	25×10^{-3}	25	7 in.	2⅜ in.	20 per sec	$1·5\times10^{11}$	Van de Graaff	300	2·5–30	concrete 240 lb., 15 ft.
4	17·5	3,000 kVA	—	none	0·8	—	25 cm	10 cm	1 per 2 sec	—	cyclotron	—	—	—
—	—	—	—	—	—	—	—	—	5 per min	10^{13}	Cockcroft-Walton	60	0·3–9·6	concrete, 2 m pyrite loaded on lab. side
34	5 (10)	—	—	—	<1	—	13·9 cm	7·8 cm	4 per min	—	—	—	—	—

Table II. El

Current No.	Energy GeV	Location	Designation	Institution	Status	Cost	Focusing type	Orbit radius	Mean radius	Sectors No.	Field max k-gaus
	1	2	3	4	5	6	7	8	9	10	11
1	7·5	Hamburg, Germany	Deutsches Elektronen-Synchrotron (DESY)	Deutsches-Elektronen-Synchrotron	Design study May 1957	—	a-g	31·70 cm	50·42 cm	48	7·89
2	6·0	Cambridge, U.S.A.	Cambridge Electron Accelerator	Massachusetts Institute of Technology and Harvard University	Completion date Jan. 1960	—	strong, a-g	85·8 ft.	118·3 ft.	48	8
3	4	U.S.S.R.	—	—	Model tests 1957	—	strong, a-g	—	—	—	—
4	1·5	Ithaca, U.S.A.	The Cornell 1·5 BeV Electron Synchrotron	Laboratory of Nuclear Studies, Cornell University	Construction start Jan. 1953	~$500,000	strong, a-g	12·5 ft.	12·5 ft.	16	13·5
5	0·75 (~1·3)	Tokyo, Japan	The INS 1-BeV Electron Synchrotron	Institute for Nuclear Study, University of Tokyo	Completion date March 1960	$640,000	strong, a-g	4 m	~5·5 m	8	6·25 (10·8
6	1 (1·2)	Roma, Italy	The INFN 1-GeV Electron Synchrotron	Institute Nazionale di Fisica Nucleare	Completion date Jan. 1959	~$1,500,000	weak	3·60 m	4·37 m	4	9·26 (
7	1·2	Lund, Sweden	—	Department of Physics, University of Lund	Engineering design 1957	—	strong, a-g	3·65 m	5·30 m	16	11
8	1·4	Pasadena, California	Caltech Synchrotron	California Institute of Technology	Completion date Sept. 1956	—	weak, c-g	148 in.	—	4	13·4
9	1	Moscow, U.S.S.R.	—	Atomic Energy Institute	Model tests 1957	—	—	0·34 m	—	—	100
10	0·6	Moscow, U.S.S.R.	—	Lebedev Institute	Construction started 1956	—	—	—	—	—	—
11	0·5	Bonn, Germany	500-MeV Elektronen-Synchrotron	Physikalisches Institut der Universität Bonn	Completion date 1958	1,300,000 DM	strong, a-g	1·70 m	2·63 m	9	10

LINEAR A

Table III. Prot

Current No.	Energy MeV	Location	Designation	Institution	Status	Cost	Output Average μA	Bean Puls μsec
	1	2	3	4	5	6	7	8
1	9·99 39·95 68	Minneapolis, U.S.A.	Proton Linear Accelerator	University of Minnesota School of Physics	Completion date 68 MeV late 1955	$1,250,000	0·2 0·04 0·02	150
2	50	Harwell, England	50-MeV Proton Linac	Rutherford High Energy Laboratory, NRNS	Completion date early 1959	—	—	rate 50/se
3	50	Lemont, U.S.A.	Injector for the 12·5 BeV Synchrotron (ZGS)	Argonne National Laboratory	Completion date Jan. 1961	—	5,000	250
4	50	Long Island, U.S.A.	Brookhaven AGS Injector	Brookhaven National Laboratory	Completion date 1959	~$2,000,000	>1,000	—
5	40	Moscow, U.S.S.R.	—	Moscow Physical Institute	Completed before 1957	—	—	—
6	31·5	Los Angeles, U.S.A.	32-MeV Linac	University of Southern California	Completion date Summer 1959	Original at Berkeley ~$2,000,000+ reinstallation cost $500,000	at 15 pps 0·2	400
7	21	Kharkov, U.S.S.R.	—	Ukrainian Technical Institute	Completion date 1950	—	—	4/se
8	20	Moscow, U.S.S.R.	(Injector for 7-GeV Synchro-phasotron)	Thermotechnical Institute	Construction started 1957	—	—	—

ble II. **Electron Synchrotrons**

tors lo.	Field max k-gauss	Power Input kW	Weight of Iron tons	Storage system	Rise Time sec	Weight of Copper tons	Aperture Width	Aperture Height	Pulse Rate	Output part./ pulse	Injector System Type	Input to RF kW	Frequency Mc/s	Shielding
0	11	12	13	14	15	16	17	18	19	20	21	22	23	24
8	7·89	1,800	600	resonant circuit	8 m	80	—	—	50 per sec	10^{11}	linear accelerator	400	499·67	earth equiv. direct 10 m, roof 2·50 m
8	8	1,200	350	capacitors choke	1/120 sec	55	6·0 in.	1·5 in.	60 per sec	1×10^{11}	electron linac	350	475·83	underground
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
6	13·5	250	20	—	1/100 i.e. 30 cycle	0·5	7 cm 3 in.	2·5 cm 1 in.	30	10^9	Van de Graaff	20	85–87	loaded concrete
8	6·25 (10·8)	140 (210)	53	condensers	$8{\cdot}4 \times 10^5$ gauss/sec	7·9	~15 cm	5·4 cm	21·5±2 per sec	3×10^{10}	linac	5 (50)	138·1	concrete
4	9·26 (11)	825	~95	capacitors	$\sim 25 \times 10^{-3}$	~8	22·7 cm	8·6 cm	20 per sec	—	Cockcroft-Walton	30	42.6–43.7	Concrete and iron
6	11	200	32	condensers	—	6·5	6·0 cm	3·6 cm	12·5	—	microtron	5–10	402	—
4	13·4	8,500	—	flywheel	0·25	—	10 in.	3 in.	1 per sec	10^{10}–10^{11}	pulse transformer	40	37·6–4·0	lead 4 in. in median plane only. External shielding: wall concrete 3 ft., no roof
—	100	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
9	10	75	12	condensers	8·5 m	4·8	—	—	50 per sec	—	Van de Graaff	2	161·45–163·08	—

NEAR ACCELERATORS

III. **Proton Linear Accelerators**

Output verage μA	Beam Pulse μsec	Beam Dia	Injector System			RF System				Tank Length	Tank Dia	Drift Tubes No.	Current No.
			Type	Energy keV	Output Average mA	Frequency Mc/s	RF Power kW	Power Units	RF Pulse Duration μsec				
7	8	9	10	11	12	13	14	15	16	17	18	19	
0·2 0·04 0·02	150	0·5 cm 1·0 cm 1·7 cm	60 x former	500	peak 3	202·55	600 2,200 3,200	Risnatron amplifiers	300	18 ft. 40 ft. 40 ft.	55 in. 60 in. 52 in.	42 38 25	1
—	rate 50/sec	—	Cockcroft-Walton	500	—	202·5	4,000	—	400	3 tanks 10, 20 and 20 MeV	—	—	2
5,000	250	1 in.	Cockcroft-Walton	750	50	200	2,500	1 or 2	500	110 ft.	39 in.	124	3
>1,000	—	~1 in.	cascade transformer	750	1 to 2 or more	200	2,500	triodes (TH-470)	200	110 ft.	3 ft.	124	4
—	—	—	—	—	—	—	—	—	—	—	—	—	5
: 15 pps 0·2	400	1 cm divergence 10^{-3} radians	Van de Graaff	4 MeV	1·5	202·55	at 15 pps 20	10	600	inside 40·5 ft.	inside 48 in.	46	6
—	4/sec	—	Van de Graaff	1,700	—	—	—	—	250	12·4 m	—	—	7
—	—	—	—	—	—	—	—	—	—	—	—	—	8

Table III. **Proto**

Current No.	Energy MeV	Location	Designation	Institution	Status	Cost	Output Average μA	Beam Pulse μsec
	1	2	3	4	5	6	7	8
1	9·99 39·95 68	Minneapolis, U.S.A.	Proton Linear Accelerator	University of Minnesota School of Physics	Completion date 68 MeV late 1955	$1,250,000	0·2 0·04 0·02	150
2	50	Harwell, England	50-MeV Proton Linac	Rutherford High Energy Laboratory, NRNS	Completion date early 1959	—	—	rate 50/se
3	50	Lemont, U.S.A.	Injector for the 12·5 BeV Synchrotron (ZGS)	Argonne National Laboratory	Completion date Jan. 1961	—	5,000	250
4	50	Long Island, U.S.A.	Brookhaven AGS Injector	Brookhaven National Laboratory	Completion date 1959	~$2,000,000	>1,000	—
5	40	Moscow, U.S.S.R.	—	Moscow Physical Institute	Completed before 1957	—	—	—
6	31·5	Los Angeles, U.S.A.	32-MeV Linac	University of Southern California	Completion date Summer 1959	Original at Berkeley ~$2,000,000+ reinstallation cost $500,000	at 15 pps 0·2	400
7	21	Kharkov, U.S.S.R.	—	Ukrainian Technical Institute	Completion date 1950	—	—	4/se
8	20	Moscow, U.S.S.R.	(Injector for 7-GeV Synchro-phasotron)	Thermotechnical Institute	Construction started 1957	—	—	—
9	10	Warsaw, Poland	—	Central Polish Nuclear Research Institute	In operation	—	—	—
10	9·9	Berkeley, U.S.A.	Bevatron 10-MeV Injector	University of California Radiation Laboratory	Completed Nov. 1953	$400,000	330	500

Table IV. **Electr**

Current No.	Energy GeV	Location	Designation	Institution	Status	Cost	Output Average μA
	1	2	3	4	5	6	7
1	45	Stanford, U.S.A.	"M" Electron Linear Accelerator	Stanford University	Design study 1956–1957	—	3
2	1	Orsay, France	Accelerator Lineaire, D'Orsay	Laboratoire des Hautes Energies et de Physique des Solides	Completion date 1960	1,500,000,000 francs	1
3	1	Kharkov, Russia	—	Ukrainian Technical Institute	Model tests 1956	—	—
4	700 MeV	Stanford, U.S.A.	Mark III Electron Linear Accelerator	High Energy Physics Laboratory, Stanford Lab.	Completion Spring 1952	$3,000,000	1

* The information given in this Reference Sheet has been compiled in the main from ORNL Report thro

III. Proton Linear Accelerators

utput verage μA	Beam Pulse μsec	Beam Dia	Injector System			RF System				Tank Length	Tank Dia	Drift Tubes No.	Current No.
			Type	Energy keV	Output Average mA	Frequency Mc/s	RF Power kW	Power Units	RF Pulse Duration μsec				
7	8	9	10	11	12	13	14	15	16	17	18	19	
0·2 0·04 0·02	150	0·5 cm 1·0 cm 1·7 cm	60×former	500	peak 3	202·55	600 2,200 3,200	Risnatron amplifiers	300	18 ft. 40 ft. 40 ft.	55 in. 60 in. 52 in.	42 38 25	1
—	rate 50/sec	—	Cockcroft-Walton	500	—	202·5	4,000	—	400	3 tanks 10, 20 and 20 MeV	—	—	2
5,000	250	1 in.	Cockcroft-Walton	750	50	200	2,500	1 or 2	500	110 ft.	39 in.	124	3
>1,000	—	~1 in.	cascade transformer	750	1 to 2 or more	200	2,500	triodes (TH-470)	200	110 ft.	3 ft.	124	4
—	—	—	—	—	—	—	—	—	—	—	—	—	5
15 pps 0·2	400	1 cm divergence 10^{-3} radians	Van de Graaff	4 MeV	1·5	202·55	at 15 pps 20	10	600	inside 40·5 ft.	inside 48 in.	46	6
—	4/sec	—	Van de Graaff	1,700	—	—	—	—	250	12·4 m	—	—	7
—	—	—	—	—	—	—	—	—	—	—	—	—	8
—	—	—	—	—	—	—	—	—	—	—	—	—	9
330	500	¼ in.	Cockcroft-Walton	480	total 10, protons 5	202·5	500	Eimac 3W 10,000	600	20 ft.	42 in. cavity	42+two ½	10

IV. Electron Linear Accelerators

	Output Average μA	Beam Pulse μsec	Beam Dia	Injector System			RF System				Acc. Length	Acc. Dia	Current No.
				Type	Energy keV	Output mA	Frequency Mc/s	RF Power Peak kW	Power Units	RF Pulse Duration μsec			
	7	8	9	10	11	12	13	14	15	16	17	18	
	3	2	½ in.	electron gun	100	1,000	2,856	20,000,000	Klystrons	2	10,000 ft.	4 in. OD	1
0	1	0·1–1	1 cm	electron gun	40	peak 100	2,997·92	320	16 Klystrons	2	—	—	2
	—	—	—	—	—	—	—	—	—	—	—	—	3
	1	1	0·5 cm	pulsed	80	250	2,856	300,000	21 Klystrons	2	220 ft.	3·247 in. ID	4

RNL Report No. 2644 (Nov. 7th, 1958) and represents an essentially complete record of all principal machines in each country throughout the world.

Table V. **Fixed-Freq**

Current No.	Particles	Energy MeV	Location	Designation	Institution	Status	Cost	Pole Tip Dia.	Field Gap	Field k-gauss
	1	2	3	4	5	6	7	8	9	10
1	Protons	850	Oak Ridge, U.S.A.	Southern Regional Accelerator (Injector)	Oak Ridge National Laboratory	Design study began 1957	—	—	—	22 max.
2	Protons	400	Gainesville, Fla., U.S.A.	University of Florida Spiral Ridge Cyclotron	University of Florida	Design study June 1958	$5,000,000 (est'd.)	—	8 in.	10 max.
3	Deuterons Protons Alphas Heavy ions	15–60 7½–115 30–120 equiv.	Berkeley, Calif., U.S.A.	—	University of California Radiation Laboratory	Completion date July 1961	—	88 in.	7 in. min. 11 in. max.	17 average
4	N^{3+} N^{4+} He^{+} $\frac{1}{2}D_2^{+}$	110 200 44 22	Zürich, Switzerland	ETH 300-cm Cyclotron Project	Swiss Federal Institute of Technology	Engineering design to start July 1959	—	300 cm	36 cm min.	centre 16
5	Heavy ions	8–10	Dubna, U.S.S.R.	Heavy-Ion Cyclotron	Joint Nuclear Research Institute & Nuclear Reactions Laboratory	Construction started 1958	—	300 cm	—	—
6	Protons N^{4+} Heavy ions	1–75 4–100 >100	Oak Ridge, U.S.A.	Oak Ridge Relativistic Isochronous Cyclotron	Oak Ridge National Laboratory	Completion date 1960	$3,000,000	76 in.	7·5 in. centre	1·8–17 average
7	Protons Deuterons Alphas	70 35 70	San Francisco, Calif., U.S.A.	NRDL Cyclotron	U.S. Naval Radiological Defense Laboratory	Completion date 1962	$1,515,000	—	~5 in. centre	B=17
8	Protons	25–50	Los Angeles, Calif., U.S.A.	The UCLA 50-MeV Cyclotron	University of California	Completion date 1959	$60,000 (excluding control desk)	44 in.	6 in. centre	26 max.
9	Protons N^{4+}	40 45	East Lansing, Mich., U.S.A.	Michigan State University 64-in. Cyclotron	Michigan State University	Completion expected June 1961	$1,500,000	64 in.	6 in. centre	17 max.
10	Deuterons	15–40	Ann Arbor, Mich., U.S.A.	86-in. Spiral-Pole Cyclotron	University of Michigan	Model tests 1958	—	83 in.	—	—
11	Protons Deuterons Alphas	30 20 40	Boulder, Color., U.S.A.	University of Colorado 52-in. Cyclotron	University of Colorado	Completion date 1961	$750,000	52 in.	7½ in. centre	15 average
12	N^{3+}	27	Oak Ridge, U.S.A.	The ORNL 63-in. Cyclotron	Oak Ridge National Laboratory	Completion date May 1952 (first beam)	—	63 in.	6 in. centre	15·5 max.
13	Protons	25	Oak Ridge, U.S.A.	The ORNL 86-in. Cyclotron	Oak Ridge National Laboratory	Completion date Nov. 1950 (first beam)	$700,000 (plus existing equipment)	86 in.	17·5 in. centre	9 max.
14	N^{3+} Alphas	25 13·6	Leningrad, U.S.S.R.	—	Physical-Technical Institute	Completion before 1957	—	120 cm	—	—
15	Protons Deuterons Alphas Heavy ions	12 24 48 equiv.	Berkeley, Calif., U.S.A.	Crocker Laboratory 60-in. Cyclotron	University of California	Completion date 1939	—	72 in.	9¾ in. centre	19·7 max.
16	Protons Deuterons Alphas	11 22 44	Gif sur Yvette, France	Cyclotron de Saclay	Centre d'Etudes Nucléaires	Completion date 1953	300 million francs	70 in.	11·8 in. centre	18 max.
17	Deuterons	22	Stockholm, Sweden	The Stockholm 225-cm Cyclotron	Nobel Institute of Physics	Completion 1951 (first beam at full radius)	~$500,000 (excluding building) rough estimate	211 cm	34·8 cm centre	20 max.
18	Deuterons Alphas Protons (H_2^{+})	21·6 43·2 10·8	Lemont, U.S.A.	ANL 60-in. Cyclotron	Argonne National Laboratory	Completion date June 1952	$950,000 cyclotron $840,000 building and facilities	62 in.	14 in. centre	14·9 max.
19	Protons Deuterons Alphas	11 22 44	Seattle, U.S.A.	The University of Washington 60-in. Cyclotron	The University of Washington	Completion date October 1952	$900,000	60 in.	10 in. centre	19 max.
20	Deuterons Heavy ions	22 100	Moscow, U.S.S.R.	Moscow 60-in. Cyclotron	Atomic Energy Institute	Completion date 1949	—	59 in.	7 in. centre	13·6 max.
21	Protons Deuterons Alphas	7·5–15 15–21 30–42	Tanashi-Machi Tokyo, Japan	The UTINS 63-in. Cyclotron	Institute for Nuclear Study	Completion date Sept. 1957 (first beam)	$650,000	160 cm	25 cm centre	13·3 max.
22	Deuterons	20	Orsay, France	Variable Energy Cyclotron	Laboratoire de Physique Nucléaires	—	—	—	—	—
23	Protons Deuterons Alphas Heavy ions	10 20 40 10/mc	Birmingham, England	The Nuffield Cyclotron	University of Birmingham	Completion date 1949	—	61·5 in.	10 in. centre	18 max.
24	Deuterons	20	Long Island, U.S.A.	BNL 60-in. Cyclotron	Brookhaven National Laboratory	Completion date April 1951	~$950,000	62 in.	10 in. centre	15 max.
25	Deuterons Alphas Protons	20 40 10	Cleveland, U.S.A.	NASA 60-in. Cyclotron	Lewis Research Centre (Nat'l. Aero. & Space Adm.)	Completion date July 1956	$1,000,000	60 in.	12 in. centre	17 max.
26	Protons Deuterons Alphas	10 20 40	Pittsburgh, U.S.A.	University of Pittsburgh Cyclotron	University of Pittsburgh	Completion date 1946	$200,000	47 in.	4½ in. centre	18 max.
27	Deuterons	16	Pretoria	The CSIR	Nuclear Physics	Completion	£100,000	44·5 in.	5 in.	17·5 max.

YCLOTRONS

ixed-Frequency Cyclotrons

d	Field k-gauss	Weight of Iron tons	Winding	Coolant	D Dia.	D Aperture	D-D Gap	Oscillator Output kW	Ion Source	Shielding	RF Frequency Mc/s	Current No.
	10	11	12	13	14	15	16	17	18	19	20	
	22 max.	2600	—	—	—	—	—	—	—	—	—	1
.	10 max.	—	—	—	—	—	—	—	—	—	—	2
nin. nax.	17 average	258	hollow copper	water	40 in.	2 in.	4 in.	—	—	concrete 8 ft.	6–23	3
m .	centre 16	625	tubing	water	250 cm	10 cm	—	300	Oak Ridge	concrete 165 cm	—	4
	—	—	—	—	—	—	—	—	—	—	—	5
n. re	1·8–17 average	200	bar 1·13 sq. in. hole 0·75 in.	water	35·5 in.	1·87 in.	2 in.	500	Oak Ridge	concrete 7–8 ft.	7·5–22·5	6
n. re	B=17	—	hollow copper	water	—	—	—	—	—	concrete 5 ft.	—	7
. re	26 max.	40	1 in. hollow	water	1½ in.	—	—	—	—	2 ft. iron all round	—	8
. re	17 max.	~75	—	—	62 in.	2 in.	—	—	—	—	—	9
	—	342	hollow bar	water	—	—	—	150	—	—	—	10
n. re	15 average	85	copper	water	24 in.	1½ in.	1 in.	80	hooded	concrete 7 ft.	7–23	11
. re	15·5 max.	—	solid copper strip	circ. oil bath	25·5 in.	3·5 in.	2 in.	—	Oak Ridge	none, exclusion area	4·9	12
in. re	9 max.	350	solid strip 3×0·4 in.	circ. oil bath	70 in.	6 in.	4 in.	250	Oak Ridge	concrete 5 ft.	13·4	13
	—	—	—	—	—	—	—	—	—	—	—	14
n. re	19·7 max.	196	copper	oil	26½ in.	2⅝ in.	3 in.	250	capillary	water 5 ft.	12	15
in. re	18 max.	252	hollow copper bar	deionized water	60 in.	6·7 in.	3·1 in.	60	Oak Ridge	underground, 6 ft. concrete	10·6	16
cm re	20 max.	370	28×25 mm bar 11 mm hole	water	190 cm	at centre 12 cm	12 cm	~180	moderately open arc	underground 2 m water on top	—	17
n. re	14·9 max.	265	aluminium	demineralized water	29½ in.	2½ in.	4 in.	70–100	hooded, arc, d.c. filament	150 lb. concrete 7 ft. walls, 4 ft. roof	11·2	18
n. re	19 max.	200	copper	oil	53 in.	2·4 in.	3·5 in.	100	graphite, enclosed with virtual cathode	sides 10 ft. earth or 4 ft. concrete; top 1 ft. concrete and 3 ft. water	11·6	19
n. re	13·6 max.	330	—	air	—	—	—	130	slit	water 1 m	—	20
cm re	13·3 max.	243	solid strip 2×32 and 2·2×28 mm	oil bath	80 cm	7 cm	10 cm	120	Oak Ridge	concrete, 150 cm sides and 96 cm top	84–12·1	21
.	—	—	—	—	—	—	—	—	—	—	—	22
in. re	18 max.	250	strip	air	28·5 in.	5 to 3 in.	3 in.	100	hooded arc	concrete and water	—	23
in. re	15 max.	240	bar 2⅜×1½ in. Al strap	water	—	4 in.	3 in.	not measured	arc (hot cathode)	loaded concrete 4–5 ft.	11	24
in. re	17 max.	225	copper	water	not circular	4·37 in.	4·3 in.	400	Berkeley	concrete 13 in. earth 4 ft.	—	25
in. re	18 max.	—	copper strip	oil	23 in.	—	1½ in.	50	capillary arc	water and earth	11·8	26
	17·5 max.	73·9	hollow core	distilled	100 cm	5 cm	6 cm	6·5			11 cm	

	Protons	10			Aero. & Space Adm.)	July 1956				
26	Protons Deuterons Alphas	10 20 40	Pittsburgh, U.S.A.	University of Pittsburgh Cyclotron	University of Pittsburgh	Completion date 1946	$200,000	47 in.	4½ in. centre	18 max
27	Deuterons	16	Pretoria, S. Africa	The CSIR 44·5-in. Cyclotron	Nuclear Physics Div. Council for Scientific and Industrial Research	Completion date January 1958	£100,000	44·5 in.	5 in. centre	17·5 ma
28	Protons Deuterons Alphas	8 16 32	Washington, U.S.A.	Dept. of Terrestrial Magnetism 60-in. Cyclotron	Carnegie Institute of Washington	Completion date 1944	$250,000	60 in.	12 in. centre	16 max
29	Deuterons Protons Tritons He^3 Alphas	6–16 3–9 12 9–27 12–32	Los Alamos, U.S.A.	Los Alamos Variable Energy Cyclotron	Los Alamos Scientific Laboratory	Completion date December 1954	—	42 in.	4·5 in. centre	18·5 ma
30	Deuterons	16	Cambridge, Mass., U.S.A.	Markle Cyclotron	Mass. Institute of Technology	Completion date (first beam) 1940	$100,000	42·5 in.	5·5 in. centre	17·4 ma
31	Deuterons	16	Zagreb, Yugoslavia	—	Institut Ruder Bošhović	Eng. design January 1958 Construction under way	$300,000 (including building)	140 cm	20 cm centre	18 max
32	Protons Deuterons Alphas	7·6 15·2 30	Kyoto, Japan	Kyoto Cyclotron	Institute for Chemical Research, University of Kyoto	Completion date January 1956	87,000,000 yen	105 cm	13·4 cm centre	17·5 ma
33	Deuterons Alpha particles Protons	15 30 7·5	London, England	MRC Cyclotron	Medical Research Council	Completion date July 1955	£150,000	50 in.	6 in. centre	15 max
34	Protons Deuterons Alphas Tritons	2·6–14·6 5·2–18·3 10·3–36 7·7–12·3	Livermore, U.S.A.	UCRL Livermore 90-in. Cyclotron	University of California Radiation Laboratory	Completion date February 1955	$1,000,000	228 cm 90 in.	305 cm centre 12 in. centre	9 max
35	Protons Deuterons	8–15 11	New York, U.S.A.	Columbia University 36-in. Cyclotron	Columbia University Pupin Cyclotron Laboratory	Remodelled 1939–40	$28,000 (1937)	36 in.	5·875 in. centre	17·5 ma
36	Protons Deuterons Alphas	7·2 14 28	Zürich, Switzerland	ETH Cyclotron	Federal Institute of Technology, Physics Dept.	Completion date 1944	approx. $100,000	33 in.	8 in. centre	19·8 ma
37	Deuterons	13·5	Kiev, U.S.S.R.	—	Ukranian Physical Institute	Completion before 1956	—	—	—	—
38	Deuterons	14	Moscow, U.S.S.R.	—	Thermotechnical Institute	Completion 1949	—	120 cm	—	—
39	Deuterons	12·7	Louvain, Belgium	Cyclotron du Centre de Louvain	Centre de Physique Nucléaire de l'Université de Louvain	Construction started 1949	—	101·5 cm	15 cm centre	18·1 m
40	Deuterons Alphas	13 26	Heidelberg, Germany	Heidelberg Cyclotron	Max Planck Institut für medizinische Forschung	Completion First 1944 Second Sept. 1956	1,500,000 DM	101 cm	27 cm centre	17 ma
41	Deuterons Alphas	12·5 25	Sofia, Bulgaria	—	—	—	—	120 cm	—	14 ma
42	Deuterons Alphas	12·5 25	Peiping, China	—	Institute of Atomic Energy	Completion date 1958	—	120 cm	—	14 ma
43	Deuterons Alphas	12·5 25	Prague, Czechoslovakia	—	Institute of Nuclear Physics Research	Completion date 1958	—	120 cm	—	14 ma
44	Deuterons Alphas	12·5 25	Dresden, E. Germany	Festfrequenz-Zyklotron Type U–120–1	Zentralinstitut für Kernphysik	Completion August 1958	—	120 cm	17 cm centre	17 ma
45	Deuterons Alphas	12·5 25	Cracow, Poland	—	Institute of Nuclear Research	Completion date 1958	—	120 cm	—	14 ma
46	Deuterons Alphas	12·5 25	Bucharest, Rumania	—	—	—	—	120 cm	—	14 ma
47	Protons (H_2) Deuterons Alphas	6 12 24	Copenhagen, Denmark	—	Institute for Theoretical Physics University of Copenhagen	—	—	90 cm 35 in.	11 cm centre 4·3 in. centre	17·5 m
48	Protons	12	Delft, Netherlands	12 MeV Radial-Sector Fixed Frequency Proton Cyclotron	Technical University Accelerator Division	Completion (internal beam) January 1958	—	85 cm	12 cm centre	cent 14
49	Deuterons	12	Birmingham, England	Radial Ridge Cyclotron	Birmingham University Dept. of Physics	Completion date April 1960	—	40 in.	3·25–4·25 in.	16 avera
50	Protons	11	Melbourne, Australia	Melbourne University Variable Energy Cyclotron (MUVEC)	Physics Dept., University of Melbourne	Completion (first beam) January 1957	£A35,000	39½ in.	6 in. centre	14 ma
51	Deuterons	9	Liverpool, England	Liverpool 37-in. Cyclotron	Nuclear Physics Research Lab. University of Liverpool	Completion June 1939	£8,000	88·2 cm 36 in.	19·6 cm centre 8 in. centre	18·5 m

Table VI. **Frequency-**

Current No.	Particles	Energy MeV	Location	Designation	Institution	Status	Cost	Pole Tip Dia.	Field Gap	Fie Cen k-ga
	1	2	3	4	5	6	7	8	9	1

¼ in. entre	18 max.	—	copper strip	oil	23 in.	—	1½ in.	50	capillary arc	water and earth	11·8	26
in. entre	17·5 max.	73·8	hollow core 22×28 mm	distilled water	105 cm	5 cm	6 cm	6·5	open, spare filament	4 m earth and concrete	13·25	27
2 in. entre	16 max.	200	copper	water	55 in.	6 in.	3 in.	—	hooded arc	earth and masonry	—	28
·5 in. entre	18·5 max.	70	copper	water	40 in.	1·9 in.	1·5 in.	70	similar to Oak Ridge	concrete 4–6 ft.	8·3–13·9	29
·5 in. entre	17·4 max.	total 96	copper	water	40 in.	2 in.	2 in.	70	conventional capillary arc	concrete 4 ft. walls 3 ft. ceiling	13·1	30
0 cm entre	18 max.	60	solid strip 5·6×0·34 cm	water tube pancakes	125 cm	9·6 cm	8 cm	80	similar to Oak Ridge	underground except front, 2 m concrete	—	31
·4 cm entre	17·5 max.	71·3	30×2·55 mm strip	oil bath	102·4 cm	4·8 cm	4 cm 2·6 cm between feelers	100	hooded arc	170 cm concrete, all sides and top	13·1	32
in. entre	15 max.	111	aluminium	water	50 in.	2½ in.	2½ in.	75	Oak Ridge carbon chimney	6 ft. concrete with 10 ft. lab. wall	11·3	33
5 cm entre 2 in. entre	9 max.	320	copper	oil cooled	198 cm 78 in.	6·35 cm 2·5 in.	one dee	380	Oak Ridge	concrete 5 ft. sides 2 ft. top	4·6	34
75 in. entre	17·5 max.	—	copper strip	water	33 in.	1·5 in.	1·75 in.	30	Oak Ridge	water 4 ft.	—	35
in. entre	19·8 max.	60	copper	water	31 in.	1·8 in.	8 in.	50	w-fil., 800 V	1 m water, top none, 2 m concrete lab. wall	13–16·6	36
—	—	—	—	—	—	—	—	—	—	—	—	37
—	—	—	—	—	—	—	—	—	—	water and boric acid, 1 m	—	38
5 cm entre	18·1 max.	60	copper	air-cooled	36·6 cm	5·3 cm	5 cm	—	hot cathode arc discharge type	50 cm ordinary concrete on three, 100 cm concrete and 100 cm water on fourth	13·6	39
7 cm entre	17 max.	80	rectangular tube	distilled water	90 cm	6·0 cm	4 cm	80	hooded capillary arc or PIG type	1 m water; 0·5 m concrete	12·8	40
—	14 max.	120	—	—	—	—	—	120	—	—	—	41
—	14 max.	120	—	—	—	—	—	120	—	—	—	42
—	14 max.	120	—	—	—	—	—	120	—	—	—	43
7 cm entre	17 max.	105	2×336	distilled water	60·8 cm	2·5×1 cm	2·5 cm	150	capillary arc	concrete 2·5 m	—	44
—	14 max.	120	—	—	—	—	—	120	—	concrete	—	45
—	14 max.	120	—	—	—	—	—	120	—	—	—	46
1 cm entre ·3 in. entre	17·5 max.	35	solid strip 3×0·3 cm	oil bath	42·5 cm 17 in.	5–7 cm 2–2·8 in.	5 cm 2 in.	—	capillary hooded are (spec.)	boron-loaded concrete 4·7 ft.	13	47
2 cm entre	centre 14	—	hollow aluminium 2×2 cm	water	—	—	one dee	—	—	—	21·5	48
5–4·25 in.	16 average	40	strip 1×0·2 in.	water-cooled rubber bags	41 in.	1·25 in.	single dee	45	hooded carbon arc	concrete, 4 ft.	—	49
6 in. entre	14 max.	42	1½×1×0·4 in dia. hole	degassed water	16 in.	2 in.	one dee	50	hooded arc	2–5 ft. brick and sand, 1·5 ft. water	19·9	50
·6 cm entre 8 in. entre	18·5 max.	46	copper	water	33 cm 13·5 in.	4·9 cm 2 in.	3·7 cm 1·5 in.	20	hot cathode	4 ft. concrete to front	12·5	51

requency-Modulated Cyclotrons

Field Gap	Field Centre k-gauss	Power kW	Weight of Iron tons	Winding	Coolant	D Aperture	Oscillator Input kW	Repetition Rate Pulse/sec	Ion Source	Shielding	Frequency Range Mc/s	Current No.
9	10	11	12	13	14	15	16	17	18	19	20	

45	Deuterons Alphas	12·5 25	Cracow, Poland	—	Institute of Nuclear Research	Completion date 1958	—	120 cm	—	14
46	Deuterons Alphas	12·5 25	Bucharest, Rumania	—	—	—	—	120 cm	—	14
47	Protons (H_2) Deuterons Alphas	6 12 24	Copenhagen, Denmark	—	Institute for Theoretical Physics University of Copenhagen	—	—	90 cm 35 in.	11 cm centre 4·3 in. centre	17·5
48	Protons	12	Delft, Netherlands	12 MeV Radial-Sector Fixed Frequency Proton Cyclotron	Technical University Accelerator Division	Completion (internal beam) January 1958	—	85 cm	12 cm centre	ce
49	Deuterons	12	Birmingham, England	Radial Ridge Cyclotron	Birmingham University Dept. of Physics	Completion date April 1960	—	40 in.	3·25–4·25 in.	ave
50	Protons	11	Melbourne, Australia	Melbourne University Variable Energy Cyclotron (MUVEC)	Physics Dept., University of Melbourne	Completion (first beam) January 1957	£A35,000	39½ in.	6 in. centre	14
51	Deuterons	9	Liverpool, England	Liverpool 37-in. Cyclotron	Nuclear Physics Research Lab. University of Liverpool	Completion June 1939	£8,000	88·2 cm 36 in.	19·6 cm centre 8 in. centre	18·5

Table VI. **Frequency**

Current No.	Particles	Energy MeV	Location	Designation	Institution	Status	Cost	Pole Tip Dia.	Field Gap	Fi Ce k-g
	1	2	3	4	5	6	7	8	9	
1	Protons Deuterons	730 460	Berkeley, U.S.A.	184-in. Cyclotron	Radiation Laboratory University of California	Completion 1946/1957	—	188·75 in.	14 in. centre	2
2	Protons	680	Dubna, U.S.S.R.	6-m Phasotron	Joint Nuclear Research Institute	Completion 1949/1953	—	—	60 cm centre	1
3	Protons	600	Geneva, Switzerland	600-MeV Synchro-cyclotron	CERN	Completion date Aug. 1957	10,300,000 Sw. francs (excl. building)	500 cm 197 in.	17·5 in. centre	18
4	Protons	460	South Ellis, U.S.A.	170-in. Synchro-cyclotron	Enrico Fermi Institute for Nuclear Studies	Completion date 1951	$2,500,000	170 in.	18 in. centre	1
5	Protons	440	Pittsburgh, U.S.A.	CIT 440-MeV Synchro-cyclotron	Carnegie Institute of Technology	Completion date May 1952	—	141 in.	156·2 in. centre	2
6	Protons	400	Liverpool, England	Liverpool 156-in. Synchro-cyclotron	Nuclear Physics Research Lab. University of Liverpool	Completion date 1954	£473,000	381 cm 156 in.	36 cm centre 41·1 in. centre	1
7	Protons	350	New York, U.S.A.	The Nevis Cyclotron	Columbia University	Completion date 1950	$3,000,000	164 in.	18 in. centre	
8	Protons	240	New York, U.S.A.	130-in. Synchro-cyclotron	University of Rochester	Completion date 1948	$1,362,000	130 in.	13·6 in. centre	1
9	Protons	200	Uppsala, Sweden	Uppsala Synchro-cyclotron	The Gustaf Werner Institute for Nuclear Chemistry	Completion date Dec. 1951 (first beam)	$1,000,000	230 cm 90·5 in.	25 cm centre 9·8 in. centre	2
10	Protons	175	Harwell, England	110-in. Synchro-cyclotron	Atomic Energy Research Establishment	Completion date Dec. 1949	~£250,000	110 in.	12 in. centre	1
11	Protons	168	Cambridge, U.S.A.	Harvard 95-in. Cyclotron	Harvard University	Completion date June 1949	$1,000,000 (approx.)	95 in.	11·7 in. centre	
12	Protons Deuterons	155 80	Orsay, France	Synchro-cyclotron de 150-MeV	Faculte des Sciences de Paris	Completion date June 1958	500,000,000 francs	280 cm	39 cm centre	1
13	Protons	100	Montreal, Canada	McGill Synchro-cyclotron	McGill University	Completion date 1949	not over $200,000	82 in.	7·5 in. centre	1
14	Deuterons Alphas	35 70	Bonn, Germany	Synchro-cyclotron Bonn	Institut für Kernphysik Universität Bonn	Completion date May 1958	1,500,000 DM	186·5 cm	29·7 cm centre	1
15	Deuterons	30	Buenos Aires Argentina	The Buenos Aires 71-in. Synchro-cyclotron	Comisión Nacional de la Energía Atómica	Completion date Nov. 1954	3,000,000 florins	71 in.	14 in. centre	1
16	Deuterons Alphas	28 56	Amsterdam, Netherlands	Philips' Synchro-cyclotron	Institute for Nuclear Research	Completion date Aug. 1949	—	180 cm	32 cm centre	1
17	Protons	21	Los Angeles, U.S.A.	UCLA 41-in. Cyclotron	University of California, Physics Dept.	—	—	41 in.	4·5 in. centre	1
18	Protons	20	Princeton, U.S.A.	Princeton FM Cyclotron	Princeton University	Completion date Jan. 1951	$180,000	35 in.	3·5 in. centre	

—	14 max.	120	—	—	—	—	—	120	—	concrete	—	45
—	14 max.	120	—	—	—	—	—	120	—	—	—	46
11 cm centre 4·3 in. centre	17·5 max.	35	solid strip 3×0·3 cm	oil bath	42·5 cm 17 in.	5–7 cm 2–2·8 in.	5 cm 2 in.	—	capillary hooded arc (spec.)	boron-loaded concrete 4·7 ft.	13	47
12 cm centre	centre 14	—	hollow aluminium 2×2 cm	water	—	—	one dee	—	—	—	21·5	48
·25–4·25 in.	16 average	40	strip 1×0·2 in.	water-cooled rubber bags	41 in.	1·25 in.	single dee	45	hooded carbon arc	concrete, 4 ft.	—	49
6 in. centre	14 max.	42	1½×1×0·4 in dia. hole	degassed water	16 in.	2 in.	one dee	50	hooded arc	2–5 ft. brick and sand, 1·5 ft. water	19·9	50
19·6 cm centre 8 in. centre	18·5 max.	46	copper	water	33 cm 13·5 in.	4·9 cm 2 in.	3·7 cm 1·5 in.	20	hot cathode	4 ft. concrete to front	12·5	51

Frequency-Modulated Cyclotrons

Field Gap	Field Centre k-gauss	Power kW	Weight of Iron tons	Winding	Coolant	D Aperture	Oscillator Input kW	Repetition Rate Pulse/sec	Ion Source	Shielding	Frequency Range Mc/s	Current No.
9	10	11	12	13	14	15	16	17	18	19	20	
14 in. centre	23·3	old coils 900 aux. coils 1600	4,000	old coils ½×4 in. solid Cu; aux. coils ½×½ hollow Cu	old coils oil, aux. coils water	12·3 cm 4⅞ in.	operating cond. 10	64	conventional	15 ft. concrete sides, 4 ft. concrete top	36–13	1
60 cm centre	16·8	1,000	7,200	copper bar	air	—	arc 50	80	hot cathode	concrete 6 m, rear beam 6 m of iron	26–13	2
17·5 in. centre	18·86	680	2,500	38×50 mm bar 20 mm hole	water	12 cm 4·7 in.	12 max.	55	Penning	heavy concrete 13 ft., lab. wall 19 ft.	28·75–16·4	3
18 in. centre	18·6	700	2,200	copper	water	4·5 in.	140 max.	60	d.c. hot cathode	10 ft. steel punching loaded concrete	28·5–11·3	4
156·2 in. centre	20·5	430 max.	1,460	copper	oil	4 in.	60	180–200	hot cathode	magnetic cement and 60% steel scrap; 12 ft. min. roof; 5 ft. reg. concrete	31·5–19·8	5
36 cm centre 41·1 in. centre	18·9	800	1,640	aluminium	treated water	9·6 cm 4 in.	2·9	110	hot cathode (cold cathode Sept. 1958)	sides, 6 ft. concrete and 12 ft. rock; front, 12 ft. loaded concrete, top, 6 ft. concrete	28·2–18·9	6
18 in. centre	18	550	2,000	copper	oil	5 in.	25	60	cold cathode	6 ft. concrete and 2 ft. pig iron; 8 ft. iron forward	29–17	7
13·6 in. centre	16·9	160	1,000	aluminium	water	3 in.	25	100–300	cold cathode	3 ft. concrete on top and back; 3 ft. copper on front	19·5–26·3	8
25 cm centre 9·8 in. centre	21·54	440	600	copper	water	8 cm 3·1 in.	25	240	pulsed arc	underground and iron-ore concrete	25·5–33·3	9
12 in. centre	16·2	300	670	copper strip	oil	4 in.	21	180	d.c. filament arc	underground, 6 ft. concrete roof	26·3–18·9	10
11·7 in. centre	19	160	641	copper	water	2 in.	~10	0–280	hot filament pulsed arc	3 to 8 ft. concrete	26–30	11
39 cm centre	16·26	400	650	Al 24×24 mm bar 13 mm hole water	water	20–8·5 cm	50	500	w-filament arc	concrete	25·2–20·2	12
7·5 in. centre	16·3	200	—	hollow Al bar	water	3·5 in.	—	400	cold cathode	12 ft. underground	25–20·6	13
29·7 cm centre	14·5	70	220	copper	distilled water	10 cm	25	1,800	low voltage arc	concrete, 2 m	10·7–11·2	14
14 in. centre	14·56	240	180	aluminium	water	7·5 in.	24	1,950	arc or filament	concrete 31·5 in. and water 31·5 in.	10·46–10·88	15
32 cm centre	13·72	90	170	solid strip	oil	18·2–15·7 cm	25	1,960	d.c. arc with filament	1 m concrete	10·05–10·43	16
4·5 in. centre	16·6	60	80	copper	oil	1·5 in.	10	1,000	open d.c. arc	water wall and exclusion	22–25·6	17
3·5 in. centre	19	20	40	copper strap	water	1·25 in.	6	2,000	hot filament	3 ft. heavy concrete all sides and top	25–28	18

(2) A plastic chamber with metal skeleton to give mechanical strength.
(3) A stainless steel chamber, comprising thin metallic slats.
(4) A double-walled chamber of insulating material.

Selected Design

For the 7 GeV proton synchrotron, the last alternative has been selected; it is not an ideal solution but an optimum choice. The details of construction are not complete but the pattern is defined in Fig. 6 and the following description outlines the features. A complete section of the chamber will comprise three major components which join together at an almost common radius. This construction gives easy access to the inner chamber and enables the three parts to be more easily designed to satisfy their principal duty.

The preferred material is a resin laminate, probably epoxy resin and glass, but the design is such that the stresses are low in those parts of the chamber which suffer irradiation, and the parts most affected are removable for repair or replacement. The main feature of the design of the double-walled chamber is that if the interspace is pumped to approximately the same pressure as the inner chamber there are negligible stresses on the inner chamber, and the material for its construction can be selected mainly for its vacuum properties. Similarly the degrading of the mechanical characteristics by radiation will not be as serious as if the chamber were highly stressed. It will be noted that the outer chamber is a sandwich between the magnet sector and the pole pieces, so that the requisite strength against collapse can be obtained. The presence of the pole pieces and auxiliary windings in the interspace is of no serious consequence since any outgassing does not enter the inner vacuum chamber.

In order to remove charge from the inner chamber wall the plastics will be bonded to non-magnetic stainless steel sheet which will be of strip-ply construction so that not only are the circulating currents minimized, but a minimum area of plastic surface is presented to the high vacuum.

To evacuate and maintain the vacuum chamber at 10^{-6} mm Hg is a major vacuum pumping problem as the mean diameter is 155 ft and the chamber is approximately 7½ ft wide. This will be accomplished by a combined system of roughing and diffusion pumps. On evacuating the chamber the roughing pumps will take both the inner and outer vacuum spaces down to a pressure of 10^{-2} mm Hg, when the high vacuum pumping will be brought in to take the inner chamber down to the best obtainable vacuum. The roughing pumps will continue to maintain the outer vessel at a pressure better than 10^{-2} mm Hg. The high vacuum pumping equipment comprises forty 24-in. diameter oil diffusion pumps, with refrigerated chevron baffles and sliding gate valves. The overall pumping speed is 232,000 l/sec.

KEY : (1) Magnet sector. (2) Magnet coils. (3) Pole tips. (4) Outer vacuum chamber (low vacuum). (5) Inner vacuum chamber (high vacuum). (6) Header chamber (high vacuum). (7) Pole face windings. (8) Pressure pads. (9) Pole tip jack. (10) Main pumping port. (11) Beam exit window.

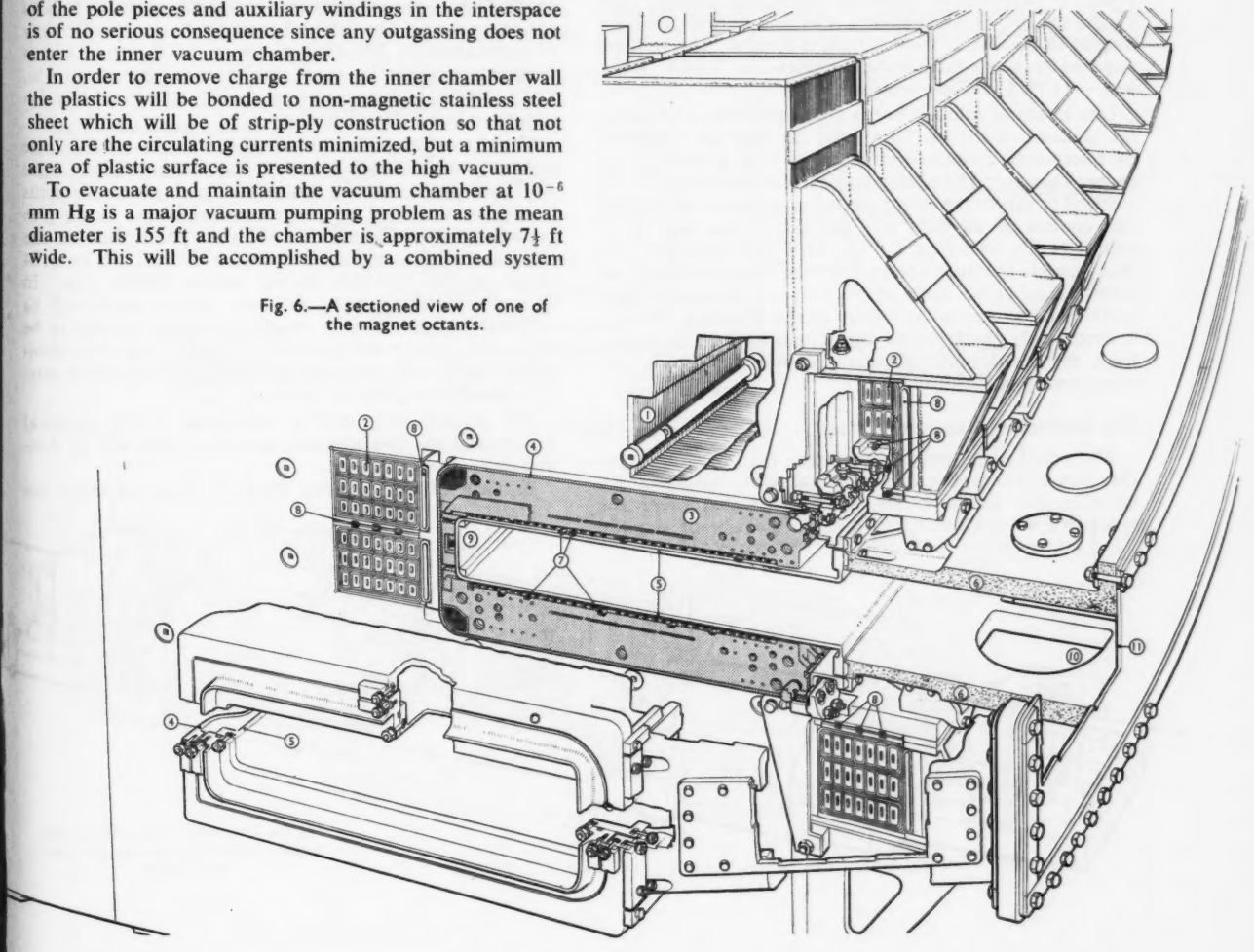


Fig. 6.—A sectioned view of one of the magnet octants.

POWER SUPPLIES

Associated with the proton synchrotron are many and varied types of power supplies but the principal one associated with the magnet presents the most interesting engineering problems. The machine will operate under a variety of conditions and the plant is being designed with a maximum flexibility. The characteristics of a standard pulse are shown in Fig. 7, where it can be seen that during each pulse, the magnet current will have to rise at approximately a constant rate to a maximum value of 9,150 amp and will subsequently fall to zero again. Facilities are required for maintaining the current at the maximum value for 0.125 sec, and for repeating the pulse at a rate of 26 pulses per minute.

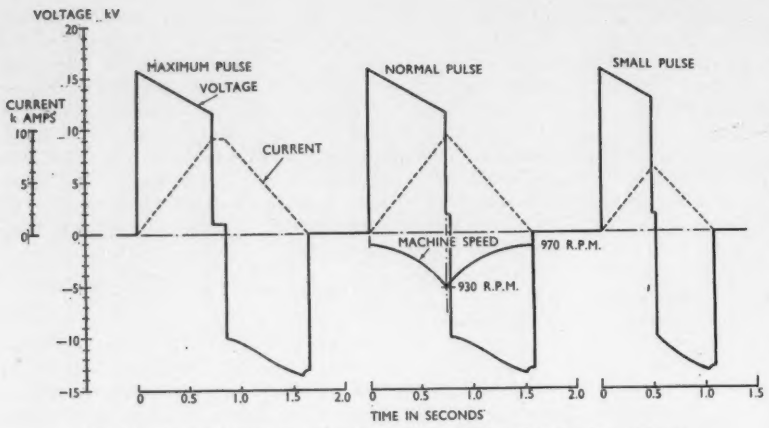


Fig. 7.—Characteristics of a standard pulse including fly-wheel speed cycle.

The energy stored in the magnetic field at maximum current is about 40 megajoules, and to take and return this energy once every two seconds to and from a public electricity supply network, would be impracticable as the surges of power would be of the order of 120 MVA; some form of energy storage, therefore, is required.

In order to produce the required current in the magnet winding during the rise time, an e.m.f. must act which can overcome the sum of the resistive and inductive voltage drops. During the flat top only a small fraction of this e.m.f. is required to maintain maximum current, and during the period when energy is being returned from the magnet to the source the e.m.f. must reverse. The voltages required for these three distinct phases are 13.9 kV, 1 kV, and −11.75 kV respectively.

One technical solution to the above problem is to isolate the demand of the machine from the electricity network by interposing a motor-alternator set with a flywheel for energy storage. The alternating current generated can be rectified to supply the direct current required by the magnet and control of the field will enable the rise time to be adjusted. By switching the rectifiers into inversion it is then possible to return energy from the magnet through the inverters so as to drive the alternators as synchronous motors and so return the energy to the flywheel. In such a circuit only the losses of the system have to be drawn from the supply network and the pulses of power are considerably reduced.

The Rutherford Laboratory Plant

The actual plant under construction for the proton synchrotron will comprise a motor, alternator, two flywheels, an alternator and a motor, arranged in that order for symmetry, reliability and to give an element of standby should one machine fail due to the exacting duty. A general impression of the plant is shown in Fig. 8. The similar halves will be mechanically coupled between the flywheels although provision is being made for the machines to be connected in electrical parallel should this prove desirable. The alternators ordered are 1,000 r.p.m., 3 ph, 50 c/s, 11.5 kV salient pole machines having a nominal rating of 60 MVA. The thermal rating of each is 46 MVA and the peak rating 79 MVA. The alternators are cooled by air in closed circuit, external fans having been selected for greater reliability under the duty of this machine. The stator frame is of fabricated construction, stayed and ribbed to form a structure of great strength. The rotor body and shaft are to be formed from a one-piece forging of high tensile nickel chrome molybdenum steel, bored through the length of its axial centre to permit inspection. The windings are specially wedged and braced not only to withstand the normally onerous conditions but severe stresses due to repeated fault conditions which could occur because of arc-back in the converter plant due to a defective excitron.

The motors ordered are of the wound rotor type each of 5,000 h.p. rating and operate at 11 kV from 3 ph 50 c/s mains. The rotors are connected to a rotor resistance to limit the power swing. The flywheel assembly has a stored energy of approximately 500,000 h.p., sec at 1,000 r.p.m., and is designed to limit the speed variation of the set to 4%. Eddy-current braking is being applied to the 40-ton flywheels to bring the set to rest.

The alternators will be connected to 96 water cooled single anode, grid-controlled mercury arc converters, via eight 12 MVA phase splitting transformers, single anode units having been selected as it was considered this would give the minimum arc-back rate. With no phase shift on the alternator shaft couplings the converters will act as a 24 phase rectifier and can deliver above 10,000 amp. In accordance with the pulse sequence the converters will be switched into inversion to enable the magnet current to be reduced to zero in the shortest permissible time thus minimizing the power loss, and increasing the repetition rate. A schematic diagram is shown in Fig. 9.

The magnet coils will be connected in two identical blocks, and the two identical converter units will be connected in alternate series.

In view of the exacting duty of these machines the

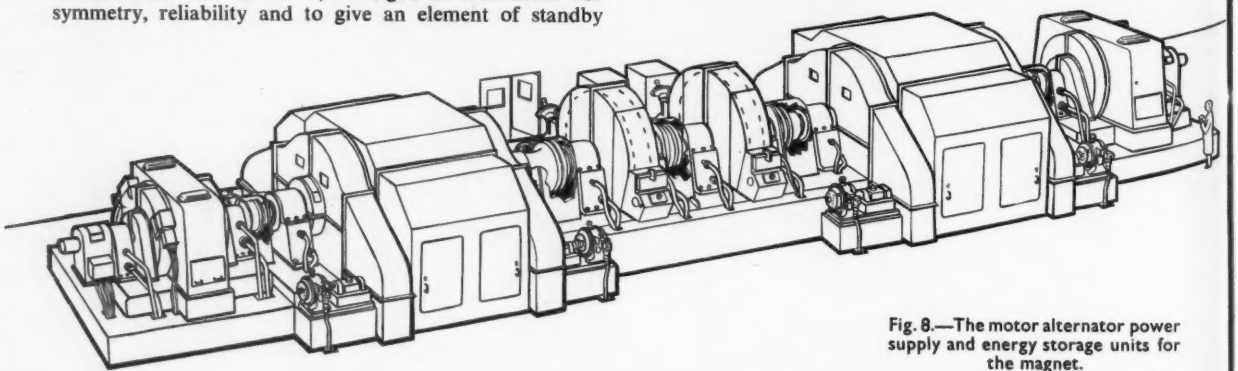


Fig. 8.—The motor alternator power supply and energy storage units for the magnet.

strictest attention is being paid to mechanical resonance on the shaft system and it is this feature which determined the choice of a 1,000 r.p.m. set. Similarly every care is being exercised in the choice of fastenings and features of mechanical construction. In view of the pulsating duty the whole is being mounted on a floating bed. This should ensure a minimum vibration to neighbouring buildings and reduce vibration stresses in machine components.

The set will be isolated from neighbouring supplies to some degree as it will be connected directly to the 132 kV grid lines via its own 20 MVA transformer. By using a flywheel set the power swing has been reduced to 10,000 kVA for a power swing of 120,000 kVA in the alternators, and the input voltage variation on the transformers due to the pulse is only ½% or 2% dependent on the number of power lines connected.

CONTROL SYSTEM AND INSTRUMENTS

The control system of the proton synchrotron has the duty of maintaining at the preselected value during successive pulses, all critical variables associated with the equipment described. It must also maintain the proper sequence of events and ensure the correct relative values of the variables during a pulse as acceleration takes place and be capable of extension to experimental apparatus. Fig. 10 gives diagrammatically the precise sequence of events.

In addition the control room will accommodate all the important instruments relative to the operation of the plant, and the control and protection of personnel. This decision to centralize controls and instruments has been taken principally because it will enable a single operator to determine quickly the operational status of the whole plant, and for him quickly to make adjustments on the basis of information. It will also permit the minimum number of staff to be engaged in machine operation and for the fault area to be quickly appreciated. Furthermore a great many components will be installed over such a large area—many in radiation areas; without an integrated control scheme it would be impossible for operators to oversee the whole project. The complete plant has therefore been interlocked in the interest of general and radiological safety and strict control will be maintained over traffic of personnel into areas of excessive radiation. As the control personnel will remain in the same situation for very long periods the control room has been located in a well screened area.

The controls for all the sections of the plant previously described will be grouped around the control room according to function, only the essential instruments and controls being located on the console. Such controls include the selection of the injection point and the peak energy, which will then operate automatically when the selected values of magnetic field are reached. The " flat top " period and pulse repetition rate which are precise time controls will also be selected. After injection, beam pick up electrodes by servo-action, control the frequency of RF acceleration required to keep the particle bunch on a stable orbit as the magnetic field and particle energy simultaneously increase.

Although centralized control has been adopted it will be necessary during the start up of the plant to carry out tests, section by section, and arrangements have therefore been made for local control panels, which can only operate when isolated completely from central control. To assist the operator an attempt has been made to follow the principle of every adjustment giving an indication on lamp or

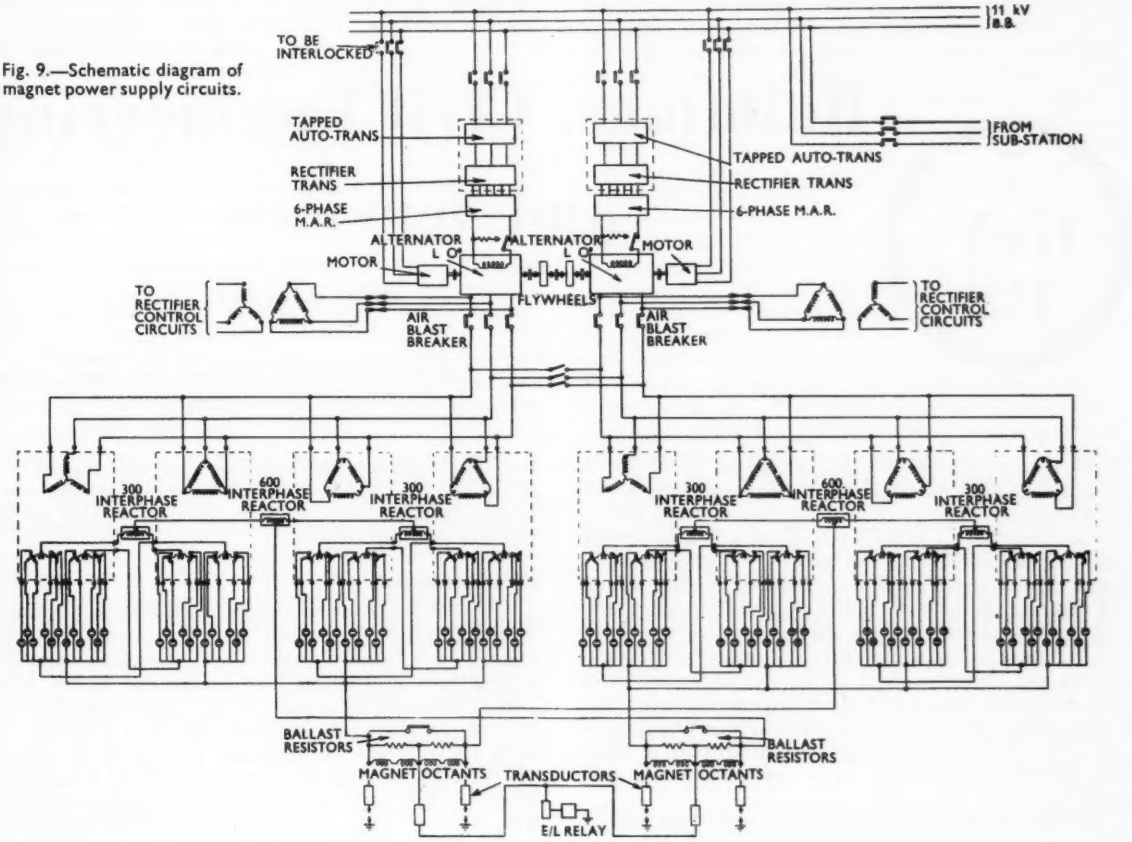


Fig. 9.—Schematic diagram of magnet power supply circuits.

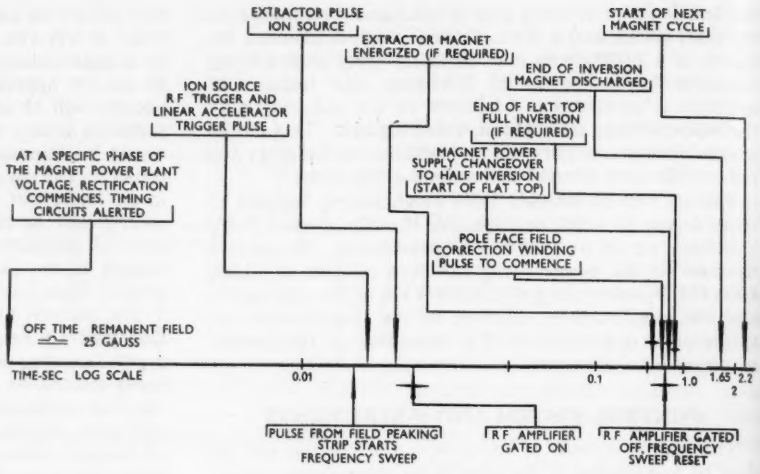

EXTRACTOR PULSE ION SOURCE
START OF NEXT MAGNET CYCLE
EXTRACTOR MAGNET ENERGIZED (IF REQUIRED)
END OF INVERSION MAGNET DISCHARGED
ION SOURCE R.F. TRIGGER AND LINEAR ACCELERATOR TRIGGER PULSE
END OF FLAT TOP FULL INVERSION (IF REQUIRED)
AT A SPECIFIC PHASE OF THE MAGNET POWER PLANT VOLTAGE, RECTIFICATION COMMENCES, TIMING CIRCUITS ALERTED
MAGNET POWER SUPPLY CHANGEOVER TO HALF INVERSION (START OF FLAT TOP)
POLE FACE FIELD CORRECTION WINDING PULSE TO COMMENCE
OFF TIME REMANENT FIELD 25 GAUSS
TIME-SEC LOG SCALE
0.01
0.1
1.0
1.65
2.2
2
PULSE FROM FIELD PEAKING STRIP STARTS FREQUENCY SWEEP
R.F. AMPLIFIER GATED ON
R.F. AMPLIFIER GATED OFF, FREQUENCY SWEEP RESET

Fig. 10.—Timing sequence for one complete pulse period plotted on a logarithmic time-scale.

meter. Similarly when a particular condition must exist for the safety of a piece of equipment it is provided with an interlock and will not depend upon memory or instruction.

The control room besides accommodating the equipment to control the machine as a whole will also be used for subsidiary control desks for radiation monitoring, beam marshalling and special experiments. Wherever possible the two types of circuit will be kept physically separate as the machine control wiring is likely to be of a more permanent nature than experimental apparatus which will require rapid installation and frequent modification.

A public address system with its microphone in the main control room will operate over the whole proton synchrotron area. In addition to normal duty arrangements the system will broadcast pre-recorded routines to ensure safety in confined areas. This audible announcement will be supplemented by visual signals, and turnstile checks.

The whole site and environs will be monitored by permanently installed radiation equipment, and the levels are to be relayed to the control room.

The operator will be assisted in his control function by being able to view the pulse shapes on oscilloscopes. He will also be able to watch the behaviour of plant in high radiation areas by the use of closed circuit television.

Acknowledgments

The author wishes to thank Dr. B. F. J. Schonland, Director of the A.E.R.E. and Dr. T. G. Pickavance, Director of the Rutherford High Energy Laboratory for their permission to publish this paper. In addition the co-operative efforts of the large team of engineers and physicists both in the U.K.AEA and industry are gratefully acknowledged as the foregoing article represents much of their collective contributions.

Buildings, Civil Engineering and Services

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THE Proton Synchrotron and its power supply plant require extensive building and civil engineering works. These comprise an injector room, a magnet room and an experimental area to house the accelerator and to provide facilities where equipment can be set up to study the properties of accelerated particles; a building housing control and counting rooms with an area attached where preparatory work in connection with experiments can be carried out; buildings to house the motor alternator plant, transformers and convertor plant; an annexe to the convertor room housing a substation and ancillary mechanical plant; a three-storey office block with laboratories on the ground floor, and a large building to be used initially for preparatory assembly and testing work and ultimately as a workshop.

With the exception of the injector room and magnet room, the buildings are of conventional steel-framed construction. The main buildings, however, present many unique features both in their construction and in the facilities provided therein.

Civil Engineering

When the synchrotron is in operation intense radiation is produced and it is, therefore, necessary to ensure that the injector and magnet rooms are adequately shielded. Furthermore, instruments must be shielded against background radiation. Semi-underground construction has been adopted for the main buildings and both concrete and earth are employed for shielding. Particle beams entering the experimental area are largely confined to a horizontal plane 6 ft 3 in. above floor level and the experimental area has, therefore, been arranged with a conventional north

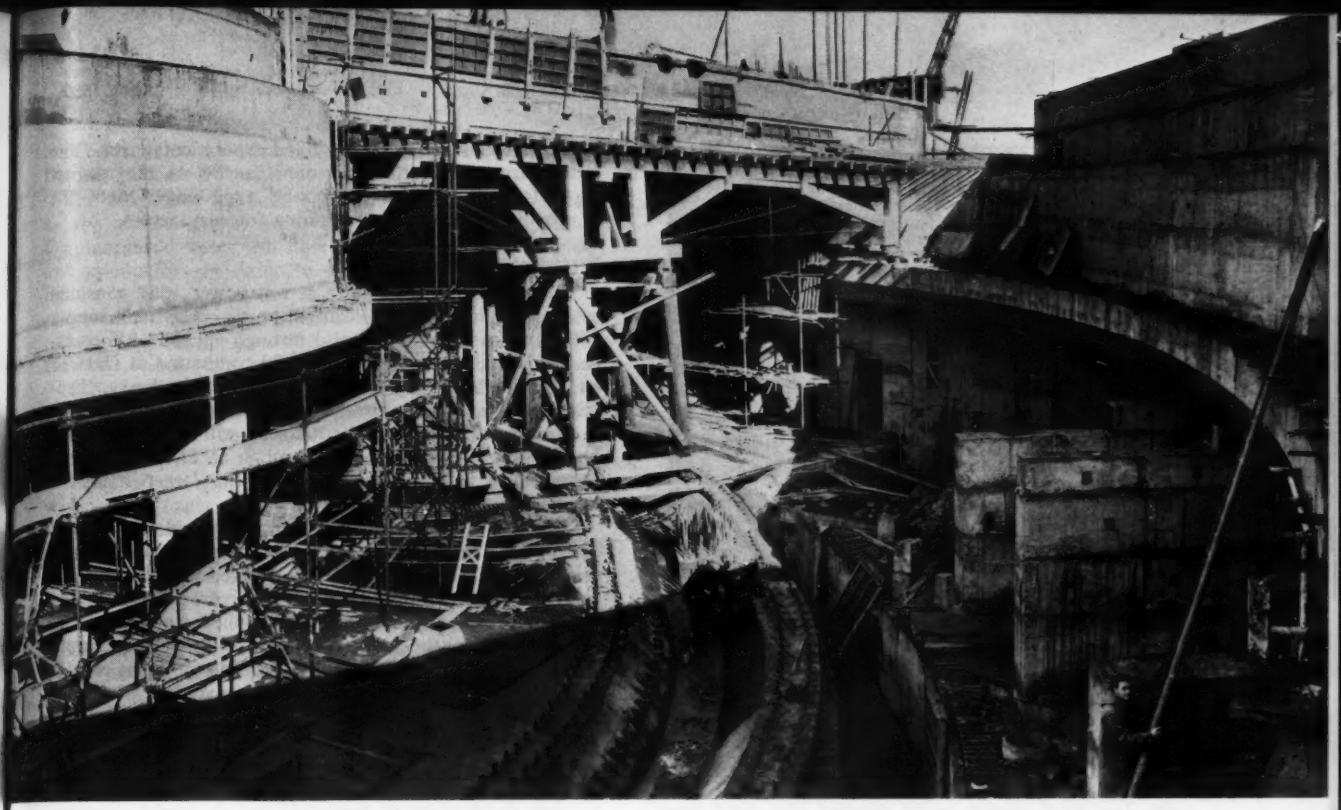


Fig. 1.—The foundations of the magnet annulus showing in the background the partially completed magnet room roof.

light truss roof so located that the path of experimental beams is directed towards an adjacent hillside.

Sub-soil. The sub-soil is fractured and weathered middle chalk to a depth of over 200 ft. The loads to be carried entail stressing the whole area of the magnet room and adjoining structures to about 2½ tons/ft². At this loading the weathered parts of the chalk yield plastically after the manner of an overloaded clay. Within 10 ft of the original ground surface the chalk is almost entirely decomposed but soon gives way to a mixture comprising about 75% lump chalk with irregular portions of the claylike decomposed chalk. The proportion of lump to decomposed chalk gradually increases with depth, but decomposed pockets were found as deep as 150 ft in boreholes.

Because of its mixed nature the sub-soil as a whole was not susceptible to laboratory experiments for strength. Tests were, however, made separately on the block chalk and on remoulded specimens of the decomposed chalk. No calculation of the behaviour of the mixed materials could be made from these but, as a matter of engineering judgment, an opinion was formed of the likely behaviour of the mixture under load.

Magnet Room. The magnet lies on an annulus of about 150 ft diameter in a room 200 ft in diameter and weighs some 7,000 tons. In order to maintain alignment of the vacuum chamber forming the accelerating orbit for protons it is required that the magnet foundation should neither hog nor sag and that it should tilt by no more than ±¼ in. across its diameter. A further requirement that the foundation as a whole should not settle in relation to adjacent buildings was relaxed in order to provide, with the sub-soil conditions obtaining, an economical building which could be built in a relatively short time. The magnet, its foundation and roof shielding impose heavy loads on the sub-soil and it was found to be uneconomical to divorce the support of the magnet itself from the ground affected by the structural loads. The foundations are, therefore, designed so as to load the sub-soil as uniformly as possible and thus minimize movement of one part at the expense of another. The foundations are divided into several units to simplify stress and load distributions and to localize horizontal thrusts from earth pressures.

The magnet itself is supported on a cellular disc foundation about 160 ft in diameter which also carries a central column and eight other columns located on a circle of 100 ft diameter. These columns transmit to the foundation a substantial portion of the weight of the magnet room roof and of the earth shielding on top of the roof. The foundation monolith self-weight is restricted by allowing substantial voids in the structure, which incidentally provide space for the accommodation of ancillary plant and for running cables and general services.

Immediately outside the magnet foundation disc, a substantial services trench is provided. The annulus of floor outside the trench is the toe of the magnet room outer wall, which is designed to take a load of 25 tons per lineal foot, being principally roof and shielding earth load.

Injector Room. The linear accelerator is housed in a reinforced concrete room 170 ft long arranged tangentially to the magnet circle. It is mounded over with earth in the same way as the magnet room and, although it is arranged on a separate foundation, connections are provided between the magnet room annular services trench and a longitudinal trench in the injector room.

Shielding Bridge. On the south side of the magnet room there is an opening 160 ft in arc length into the experimental area, but it is generally required that this opening shall be stemmed with concrete except for small apertures through which experimental beams will be guided. Up to a level of 12 ft 6 in. above the floor this shielding takes the form of a concrete wall 30 ft thick in the form of transportable blocks. The blocks are arranged in stacks of five, each block being 2 ft 6 in. deep, and their plan positions will be such that there will be no continuous straight paths between blocks permitting particles to stream from the magnet room to the experimental area. Above

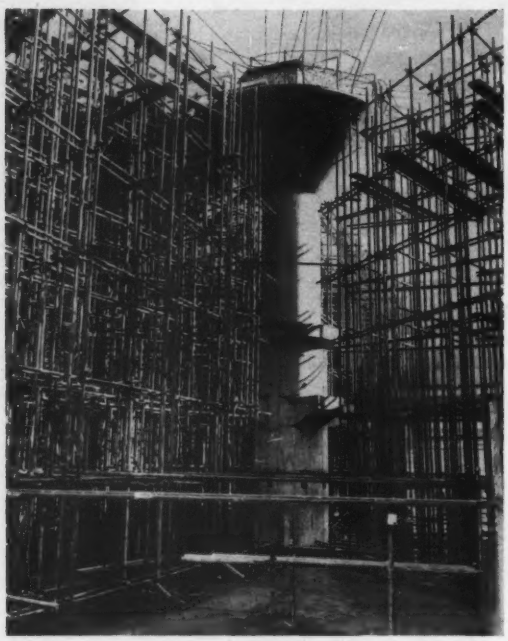


Fig. 2.—Central column, which together with eight other columns on a 100 ft circle transmits the bulk of the roof and earth shielding weight to the foundations.

the 12 ft 6 in. level a concrete shielding bridge spans the whole of the width of the opening into the experimental area. The bridge superstructure is 28 ft wide and 17 ft 6 in. high and is dog-legged in plan with supports only at each end and at the point of change of direction. A single monolith foundation supports the two abutments of the bridge and the central pier. Voids are left in this monolith and large cells are formed in the eastern abutment to achieve a balance of the complicated loadings.

If it could have been achieved economically it would have been desirable for the whole of the beam to span the opening with no central support, since this would increase the scope for beam paths available to experimenters. However, it was agreed that a central pier could be accepted provided that the projected width at beam height on a line from the magnet room to the experimental area was kept to a minimum. It proved possible to design a pier with a solid mild-steel shaft only 1 ft wide and 8 ft long with a height of 2 ft 6 in. The mid-height of the shaft is at the plane of the experimental beam and the shaft carries 7,500 tons. Above and below the mild-steel section are very heavy spreading blocks forming a cap and a pedestal, each of which comprises five heavy plate girders clad in concrete. The cap and pedestal are sized to match the module of the shielding blocks which will be placed alongside them and when necessary the open spaces around the steel shaft will be stemmed with small blocks which can be placed by a fork-lift truck or by hand.

Tunnels. The floor level of the main buildings is several feet below that of the adjacent ancillary buildings and services have, therefore, to be run in tunnels, which in some cases are taken down to such a level that they pass below the foot of the magnet room retaining wall. Separate tunnels are provided between the ancillary buildings and the magnet room for mechanical services, electric cables and conditioned air, while a tunnel from the control room branches to both magnet room and experimental area. The latter forms the normal personnel access to the magnet room from the control room and a passenger/goods lift is provided in the control building for easy access.

Electrical Services

The plant, when operating at full power, may consume as much as 20 MVA of electrical power. The main supply will be from the national grid through a 132/11-kV transformer, installed in the existing grid compound at Harwell and feeding an 11-kV switchboard located in the synchrotron substation in the annexe to the convertor room. The two motors of the motor-alternator set will be fed from this board, which will also supply, through an 11/3.3-kV transformer and a 3.3-kV switchboard, the larger items of ancillary plant.

General electrical services will be supplied through 11-kV/415-V transformers and 415-volt switchgear, but in this case the 11-kV supply will be derived from an existing substation located near to the synchrotron area. The general services will thus not be supplied from the same 11-kV input as the main plant and will not be unduly subject to the effects of the pulsed load on the latter circuit.

All services in the injector room, magnet room and experimental area are to be fed from the synchrotron 415-volt switchboard via local switch-fuseboards or direct from this board. Certain ancillary buildings will be fed at 415 volts from the existing substation already referred to, and distribution in these will be via switch-fusegear. Facilities will be provided for emergency tripping of supplies to experimental apparatus, while leaving energized the switchgear through which lighting, cranes and other non-experimental services are supplied.

Cabling. The magnet supply, with an r.m.s. current of 6,000 amp, will be taken from the excitrons in the convertor room to the coils of the magnet by means of 22-kV grade mass impregnated non-draining cables running through the electrical services tunnel and voids in the magnet foundation.

L.T. cabling will generally be of the mass-impregnated non-draining type, and multicore cabling of the Unipren type.

Lighting. The injector and magnet rooms will be lit by cold cathode fluorescent tubes, which incidentally permit economies in building costs by minimizing the clearance required between overhead cranes and the roof. Other areas of the workshop type will generally be lit by high bay fittings of the blended mercury arc-tungsten type. The control room lighting will be of the diffusing ceiling type with dimming control. Over-riding control of lighting in the magnet and injector rooms will be provided from the control room so that switching of lights can be used to indicate to personnel that start-up of the machine is imminent. This system will be backed up by sirens and flashing red warning lights. Emergency d.c. lighting will be provided in all operational and workshop areas and corridors.

Small Power Supplies. Throughout the operational and workshop areas busbar trunking is being provided, with 30 amp and 60 amp triple pole and neutral plug-in units, and special panels comprising one 15-amp and three 5-amp switched and fused outlets will be installed on walls at frequent intervals. Triple pole and neutral switch fuse units are being provided for special services at various locations in ratings up to 300 amp.

Plant Cooling

The majority of the 20 MVA of power fed into the plant must ultimately be removed by various cooling services

and both water and air cooling systems will be provided for this purpose (Fig. 5).

The main heat losses in operation will be copper losses in the main magnet coils and in the ancillary plant. Demineralized water will flow through the hollow magnet coil conductors in order to dissipate losses of approximately 4 MW, the water supply being taken from ring mains accommodated in the mechanical services trench adjacent to the magnet and fed by pipelines in tunnels from the water plant house in the convertor room annexe. The demineralized water will be cooled in a pair of surface-type heat exchangers and provision will be made for heating the magnet coil water when the magnet is not energized, in order to limit to a narrow range the temperature of the copper. Other plant, such as the vacuum pumps and experimental gear in the experimental area, will be cooled by separate demineralized water circuits connected to heat exchangers in the water plant room, while other items of plant will be supplied with raw cooling water for use either direct or in local heat exchangers.

The heat in the raw water cooling the heat exchangers and other plant will be dissipated in a battery of induced draught cooling towers rated to cool 420,000 gallons of water per hour from 95° to 79°F with a wet bulb temperature of 72°F.

Air-conditioning Plant. In order to limit distortion of the magnet sectors, arrangements are being made for them to be kept at substantially constant temperature whether on or off load, dissipating iron losses or heating as appropriate by air flow over their surfaces. Conditioned air will be forced by fans installed in the air-conditioning plant room (annexed to the convertor room) into a duct forming a ring main under the magnet foundation. Outlets from this duct are provided under each gap between magnet sectors and air from these will pass over the magnet sector surfaces to be ultimately discharged from the magnet room at roof level into a return duct. Ducting equipped with fans and heaters will allow a certain amount of air to be drawn off from the main body of the magnet room and diffused through the injector room, before returning to the magnet room.

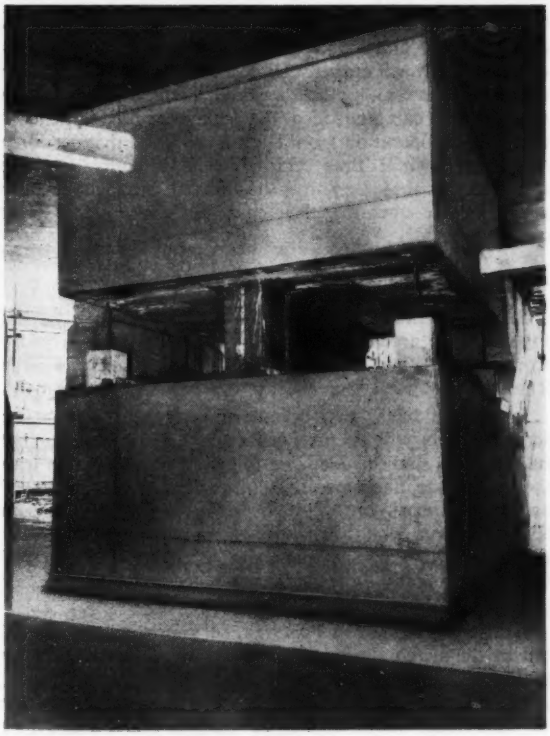


Fig. 3.—Pier with steel shaft carrying 7,500 tons.

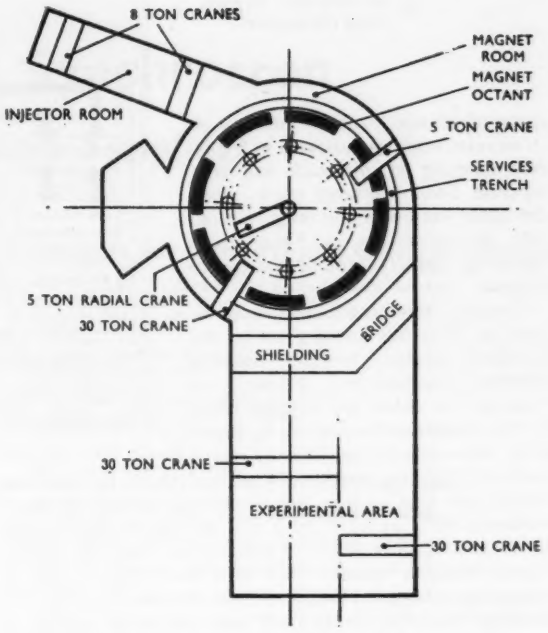


Fig. 4.—General arrangement of the lifting facilities.

At the air-conditioning plant room the return duct will be equipped with two extract fans and provision made for a normal discharge of 10% of the air circulation to atmosphere and corresponding make-up with fresh air. Full-flow air filters will be installed and the heat picked up in the magnet room will be extracted by refrigerating plant. Provision will be made for moisture extraction and subsequent reheating to ensure that there shall be no deposition of moisture on the magnet surfaces. The steam air heaters will also be capable of making good the losses from the magnet room when the plant is not operating.

Recooled water from the cooling towers will be supplied to the motor alternator house for coolers associated with the motor alternator plant and also to the phase-splitting transformers and to the excitrons in the convertor room.

Water Treatment. The clean water circuits are to be filled with water from three mixed-bed demineralizing plants which will operate in conjunction with ion exchange units for the removal of residual oxygen. Each plant is capable of treating 180 gallons per hour of raw water or 480 gallons per hour of water bled from the cooling system.

The raw water make-up for the cooling towers will be treated in a starvation base-exchange plant.

Handling Facilities

In the main buildings, two major handling problems arise, namely the setting of the magnet sectors on their foundations and the movement of concrete shielding blocks. The magnet sectors weighing approximately 20 tons will be handled in the magnet room by an overhead

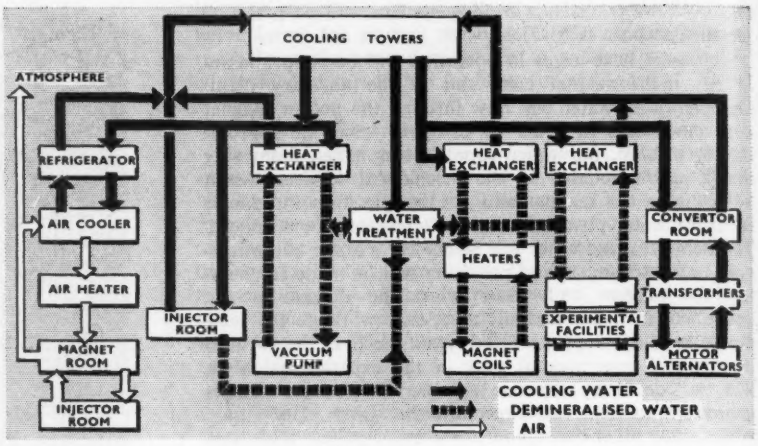


Fig. 5.—Schematic diagram of the site services.

crane of 30 tons capacity running on an annular track as indicated in Fig. 4. Also running on this track will be a separate 5-ton overhead crane, while the inner section of the magnet room will be served by a 5-ton crane operating radially around the centre column.

Concrete shielding blocks may be used to stem the opening under the shielding bridge or for building shielded enclosures, known as "igloos," in either the magnet room or the experimental area. It is, therefore, necessary to be able to move stacks of shielding blocks into position under the shielding bridge and also to turn the blocks, the largest of which measures 15 ft by 10 ft by 2 ft 6 in. and weighs 25 tons, on to any of their faces. Furthermore, since the experimental area is divided into two parts by a row of stanchions along its length, provision must be made for handling shielding blocks from one side of the stanchions to the other. Each side of the experimental area will be equipped with a 30-ton overhead crane and special handling gear provided for turning and transporting the blocks.

Block Handling Gear. To turn a block from the horizontal position on to an end or a long side it will be placed by an overhead crane on to a cradle pivoted about a horizontal axis at one end. The crane will then be attached to a bracket mounted on the free end of the block, which is slowly hoisted and traversed so that it is brought into an erect position. The cradle will be locked and the block removed by a further lift from the crane. In order to take a block from one side of the experimental area to the other, the two cranes will be used in tandem, supporting a long fabricated beam from which the block is suspended.

Trolleys and Tractors. Since the shielding blocks when in position under the shielding bridge will almost completely fill the vertical space available they cannot be put into position by any form of overhead lifting equipment. It was, therefore, necessary to devise a method of moving a stack of five shielding blocks across the floor into position with a minimum clearance lift, and it was decided to employ jacking trolleys propelled by a tractor. The lowest block of each stack will have two longitudinal slots 1 ft 6 in. wide and 1 ft 1 in. high pitched at 5 ft centres through the whole length of the block. Into each slot a pair of eight-wheeled bogies will be run on rails built into the floor and extending from the mechanical services trench in the magnet room, under the shielding bridge, and well into the experimental area. Each trolley will incorporate a hydraulic jack capable of lifting a load of 62½ tons through a vertical range of 1½ in. An independent tractor, incorporating the hydraulic pumping equipment and control gear and its own electric travelling gear, will be linked to the bogies. The tractor, whose wheels will be fitted with tyres of solid rubber, will run on the same rails as the trolleys and be able to move a complete stack of blocks weighing 125 tons at 2 ft/min. The design of equipment and the operating procedure ensure that, while the gap between adjacent blocks is kept to an absolute minimum, it will be possible to move stacks of blocks without fouling adjacent blocks. To this end, the control of the individual hydraulic jacks is arranged so that the operator can correct any tilt which may develop while the stack is being moved.

Cranes. In addition to the cranes already mentioned two 8-ton overhead travelling cranes are installed in the injector room where they will handle the parts of the linear accelerator and its associated equipment. In the preparation area adjacent to the control room is a 25-ton overhead travelling crane, which handles magnet sectors which undergo their initial testing in this area. The motor-alternator house and convertor room will have cranes of 80 tons and 10 tons capacity respectively, the former being used for erection of the motor-alternator set and for maintenance work on the phase-splitting transformers. Other ancillary buildings contain one 8-ton overhead electric travelling crane and one 5-ton and one 3-ton hand-operated overhead cranes. Of the overhead electric cranes only those in the motor-alternator house and convertor room will be cab controlled, the remainder having pendant controls for operation from floor level. The magnet room and experimental area crane pendant controllers are arranged so that they can be moved along the crane girder by the operator, thus enabling him to circumvent obstructions.

General Services

Supplies of mains water, compressed air, gas and steam, together with a condensate return system, will be provided from the existing main supplies to the Atomic Energy Research Establishment nearby.

In all buildings, gas, compressed air and cold water service points will be provided on a liberal scale so that full facilities shall be available for work in connection with the setting up and operation of experiments. A special compressed-air supply will be available in the magnet room for use in conjunction with the vacuum pumps, and in the event of failure of the main site supply this system will be automatically changed over to a stand-by air compressor.

Heating of the injector and magnet rooms will be carried out by the air-conditioning plant already described. Other buildings are heated by low-pressure hot water or steam, employing unit heaters, convectors and radiators to suit the individual requirements of the various areas. Hot water is supplied from storage-type steam-heated calorifiers or electric storage heaters.

7 GeV Proton Synchrotron

—Contractors and Suppliers

Construction of Proton Synchrotron

BRITISH BROWN BOVERI, LTD., 75 Victoria Street, London.
Converter equipment.
ENGLISH ELECTRIC CO., LTD., Magnet House, Kingsway, London.
Rotating machinery for power supply.
MARSTON EXCELSIOR, LTD., Wobaston Lane, Wolverhampton.
Development and manufacture of main vacuum vessels.
METROPOLITAN-VICKERS ELECTRICAL CO., Trafford Park, Manchester.
Manufacture of magnetic coils.
J. SANKEYS, LTD., Regent Street, London.
Magnet sectors.

BRITISH COPPER REFINERS, LTD., Prescot, Lancs.
Blister copper for magnet coil.
J. BOOTH AND SON (BOLTON), LTD., Nechells, Birmingham.
Extrusion of copper for magnet coils.
EDWARDS HIGH VACUUM, LTD., Crawley, Sussex.
High vacuum equipment for injector, main vacuum pumping equipment.
LONDON ALUMINIUM (CONTAINERS), LTD., Westwood Road, Witton, Birmingham.
R.F. liner for injector.
MATTHEW HALL AND CO., LTD., 26 Dorset Square, London.
Supply of daywork mechanical labour.
H. AND E. LINTOTT, Horsham, Sussex.
Sector test rigs, etc.
PHILIPS GLOEILAMPENFABRIKEN, Eindhoven, Holland.
Ferrite frames for R.F. unit.
S.A.M.E.S., FRANCE, Grenoble, France.
Electrostatic generator for injector.
VICKERS-ARMSTRONGS (AIRCRAFT), LTD., Vickers House, Broadway, London.
Design contract plant.

ANDERSON CLYDE ENGINEERS, Chadderston, Manchester.
25-ton mobile gantry.
BABCOCK AND WILCOX, LTD., 209 Euston Road, London.
Vacuum vessel for linear accelerator.
N. G. BAILEY, Ilkley, Yorks.
Daywork electrical labour.
BRITISH THOMSON-HOUSTON CO., LTD., Rugby, Warwickshire.
Modulator for R.F. supply to injector.
DAVID BROWN CONSTRUCTION EQUIPMENT, LTD., 96 Piccadilly, London.
Towing tractor.
CARRIMORES SIX-WHEELERS, LTD., North Finchley, N.12.
Transporter for sectors.
C. AND N. ELECTRICAL, LTD., Gosport.
Supply of electrical and electronic control equipment.
ENGLISH ELECTRIC CO., LTD., Marconi House, Strand, London.
Rectifiers for test rigs.
ELECTRO-DYNAMIC CONSTRUCTION CO., Orpington, Kent.
H.F. alternator for injector.
FIRTH-VICKERS, LTD., Weedon Street, Sheffield.
S.s. frames for linear accelerator.
GENERAL ENGINEERING (RADCLIFFE), CO., Radcliffe, Lancs.
Vacuum roughing pumps.
C. W. GLOVERS AND PARTNERS, Francis Street, London.
Consulting engineers. (Loan of staff.)
HACKBRIDGE AND HEWITTIC ELECTRIC CO., LTD., Hersham, Walton-on-Thames, Surrey.
R.F. bias support.
J. AND E. HALL, Dartford, Kent.
R.F. cavity cooling equipment.
HILGER AND WATTS, 98 St. Pancras Way, London.
Survey consultancy.
A. IMHOF, LTD., Uxbridge, Middx.
Control racks
H. AND E. LINTOTT, Horsham, Sussex.
Miscellaneous components for main machine.
LIVINGSTON LABORATORIES, Retcar Street, London.
Oscilloscopes.
MARSTON EXCELSIOR, LTD., Wobaston Lane, Wolverhampton.
R.F. cavity, experimental vacuum chamber.
MOORES (BOURNEMOUTH), LTD., Bournemouth, Hants.
Miscellaneous components for main machine.
NATIONAL PHYSICAL LABORATORY, Teddington, Middx.
Survey consultancy.
PORTSMOUTH AVIATION, The Airport, Portsmouth.
E.H.T. mechanical equipment, miscellaneous components for main machine, design contract, E.H.T. platform for injector.
TALBOT-PONSONBY, LTD., Langrish, Hampshire.
Support stand and rails for injector D.C. gun.
JOHN A. SMITH, Wolverhampton, Staffs.
Design contract (plant).
SPEEDY AND EYNON (1951), LTD., Warstone Lane, Birmingham.
Miscellaneous components for main machine.
S.A.M.E.S., FRANCE, Grenoble, France.
650-kV H.V. equipment for injector, H.V. supply for proton gun.
TECHNICAL DESIGN AND TOOL CO., Reading, Berks.
Design contract (plant).

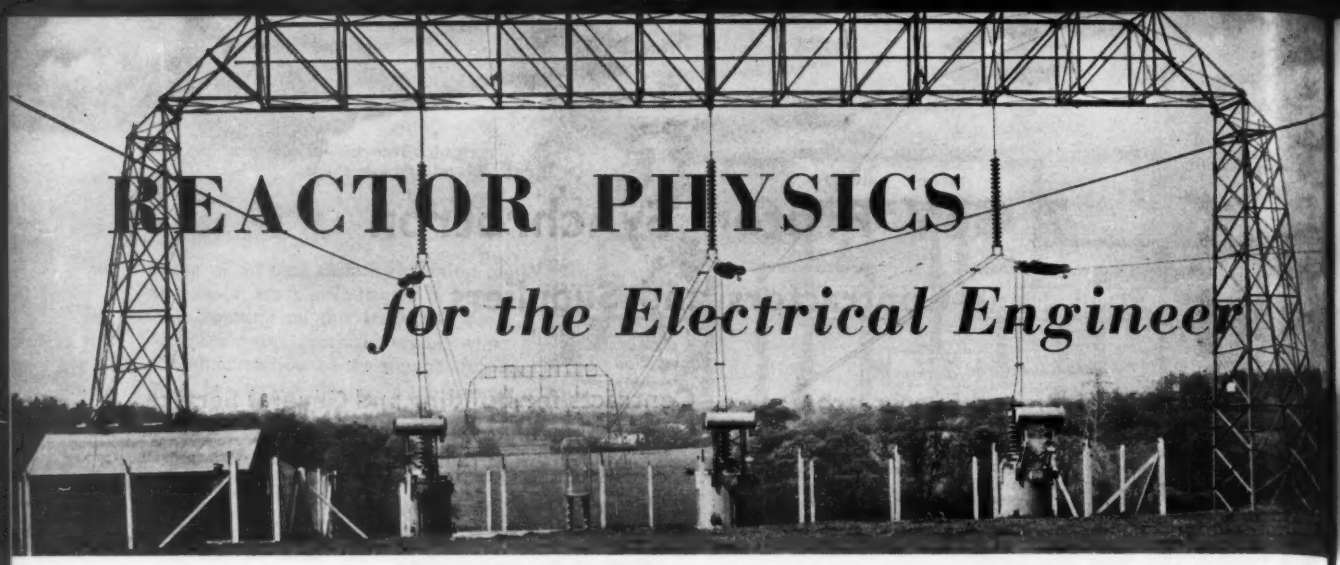
Contracts for Building and General Service

FAULKNER AND PARTNERS, 39 Bedford Square, London.
Quantity surveying.
MERZ AND McLELLAN, 32 Victoria Street, London.
Consulting engineers.

W. E. CHIVERS AND SONS, Devizes, Wilts.
Main civil contractors.

N. G. BAILEY AND CO., Ilkley, Yorks.
Lighting and small power installation.
Z. D. BERRY AND SONS, LTD., 25 Stanley Street, Warrington.
Heating and hot water services.
DUDLEY AND DOWELL, LTD., Cradley Heath, Staffs.
Metal duct covers and cellar flaps.
MATTHEW HALL AND CO., LTD., 26 Dorset Square, London.
Air-conditioning equipment.
FILM COOLING TOWERS (1925), LTD., Brentford, Middx.
Evaporative cooling units.
RUBERY OWEN AND CO., LTD., Wednesbury, Staffs.
Structural steel.
TAYLOR WOODROW CONSTRUCTION, LTD., Southall, Middx.
Arcon buildings.
WHARTON CRANE AND HOIST CO., Station Road, Reddish, Stockport.
25-ton crane assembly and test building, 3 E.O.T. cranes, magnet buildings and 5 E.O.T. cranes.
WHITEHEAD IRON AND STEEL CO., Tothill Street, London.
Reinforcing rods.

ABERFREN CABLE AND CONSTRUCTION CO., Green St., Kidderminster.
Cables.
D. ANDERSON AND CO., LTD., Stretford, Manchester.
Metal decking and waterproofing.
AYRSHIRE DOCKYARD CO., LTD., Irvine, Ayrshire.
Steel partitions.
JOHN BARNSLEY AND SONS, LTD., Netherton, near Dudley, Worcs.
Shield block lifting and turning over equipment.
J. BOOTH AND SON (BOLTON), LTD., Nechells, Birmingham.
Structural steel.
THE CEMENTATION CO., LTD., 20 Albert Embankment, London.
Exploratory boring.
COWANS SHELDON, LTD., Africa House, Kingsway, London.
80-ton O.E.T. crane, motor alternator building.
D.S.I.R., Regent Street, London.
Research on shielding beam.
DEANS BLINDS (PUTNEY), LTD., 329 Putney Bridge Road, London.
Blinds and curtains.
ENGLISH ELECTRIC CO., LTD., Marconi House, Strand, London.
Distribution switch fuseboard.
J. ERRINGTON (ENGINEERS), LTD., Sandyford Square, Newcastle-on-Tyne.
Lifting plugs for concrete shielding blocks.
EVANS LIFTS, LTD., Abbey Lane, Leicester.
Lift to control building.
W. T. GLOVERS AND CO., Francis Street, London.
Cable.
W. T. HENLEYS TELEGRAPH WORKS CO., LTD., 51 Hatton Garden, London.
Cable.
JOHNSON AND OLIVER CO., LTD., Walkergate, Newcastle upon Tyne.
Lifting plugs for concrete shielding blocks.
MELLOWES AND CO., LTD., 54 Victoria Street, London.
Dome lights.
MORELAND HAYNES AND CO., 80 Goswell Road, London.
Structural steel.
THE PERMUTIT CO., LTD., Gunnersbury Avenue, London.
Water treatment plant.
POTTER RAX, LTD., Shepperton Road, London.
Folding doors and partitions.
RAGUSA ASPHALT PAVING CO., LTD., 2 Hartopp Road, Alum Rock, Birmingham.
Built-up felt, roofing-magnet and ancillary buildings.
N. F. RAMSEY, 5 Victoria Street, London.
Ballustrades and handrails.
READ AND PARTNERS, Stamford Street, London.
Electrical installations.
RESILIENT TILE AND FLOORING (EALING) CO., LTD., 3 Replingham Road, London.
Linoleum floor covering.
A. REYROLLE AND CO., LTD., Hebburn, Co. Durham.
Switchgear.
ROBERT HUDSON, LTD., Meadow Lane, Leeds.
Shielding block trolleys and traction unit.
JOHN SMITH (KEIGHLEY), LTD., Bradford Road, Keighley.
10-ton O.E.T. crane, motor alternator building.
STERLING CABLE CO., 292 High Holborn, London.
Cables.
THOMAS SUMMERSON AND SONS, LTD., Mowden Hall, Darlington.
Rail track materials.
WILLIAM PRESS AND SONS, LTD., 22 Queen Anne's Gate, London.
Steam, gases, compressed air and cold water services.
WILLIAMS AND WILLIAMS, LTD., Reliance Works, Chester.
Metal windows and curtain walling.
YORKSHIRE ELECTRIC TRANSFORMERS, LTD., Dewsbury, Yorks.
Transformers.



REACTOR PHYSICS
for the Electrical Engineer

Part I.

By J. C. JAMES, M.A.
(CEGB, R. and D. Department)

In this two part article, a new approach is made to one-group reactor physics. The concept of "buckling" is abandoned in favour of expressions more familiar to the electrical engineer.

TRADITIONALLY in a discussion of elementary Reactor Physics, as described by one-group theory, the mathematical ideas and terminology involved in chain reactions and neutron kinetics are carried over into reactor system theory. There exist, however, in electrical engineering the fundamentals of a long established and much used branch of science which closely parallels elementary reactor theory. It is widely known but to those unfamiliar with its terminology it may be said that the ideas involved have something to offer in ease of understanding.

The concepts of flux and current analogous to electric potential and current are already used in reactor theory and are derived from a consideration of neutron kinetics.

Mean Free Path, Mean Square Path

Neutrons are produced from the fission process with a high average velocity. There is no favoured direction initially or after collisions and hence spherical symmetry exists. Fission is itself initiated by the collision of neutrons with the nuclei of fuel atoms, but more easily by neutrons of the lower velocities. These are produced by allowing the fast neutrons to collide with the nuclei of lighter elements mixed with the fuel and chosen for their low absorbing property (e.g. graphite, beryllium, hydrogen). The neutrons then diffuse further at thermal energies experiencing a number of scattering collisions until they suffer an absorbing collision (which may or may not cause fission, depending on the absorbing nucleus). Because the movements are so complex they are treated by probability methods, i.e. by estimating representative values of the quantities concerned.

The probability of a neutron striking a nucleus is measured by the "equivalent target area" or cross-section of the nucleus. There is a cross-section Σ_s related to scattering and a cross-section Σ_a related to absorption. From the scattering cross-section the mean free path between collisions may be deduced, and from this the rate of diffusion and the radial distance travelled before absorption.

For a given neutron velocity there is a probability $\Sigma_s dx$ that it will collide with a nucleus during its flight over dx cm in a given medium and a probability $(1-\Sigma_s dx)$ that it will not. In a length x it will undergo this trial x/dx times.

The probability of it not colliding during x cm but colliding in the next dx is:

$$p=(1-\Sigma_s dx)^{x/dx}\, dx$$

As $dx \to 0$

$$p \to \Sigma_s \exp(-\Sigma_s x)\, dx$$

by definition of the exponential function. The total probability of collision somewhere is:

$$P=\int_0^\infty p dx = 1$$

The mean distance travelled by all such neutrons between collisions is:

$$\lambda=\int_0^\infty px\,dx=\int_0^\infty \Sigma_s x \exp(-\Sigma_s x)dx = 1/\Sigma_s$$

The mean square value of these distances is:

$$s^2=\int_0^\infty px^2 dx=\int_0^\infty \Sigma_s x^2 \exp(-\Sigma_s x)dx$$
$$=2/\Sigma_s^2=2\lambda^2$$

Spherical Symmetry

The vectors representing the free paths of all the neutrons have spherical symmetry to a close approximation.

Their projections on the x axis may be considered in groups having the same length (see Fig. 1). In the positive

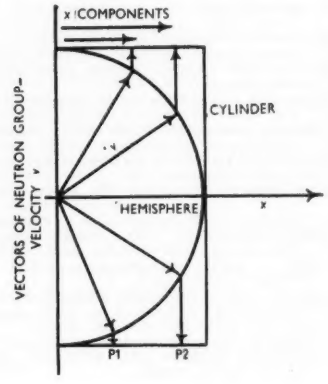


Fig. 1.—Projections of the neutron free path vectors on the x-axis.

and negative directions separately, vectors normal to the x direction may be added to the free path vectors (without altering the x component) so as to bring the resultants onto the surface of a cylinder. The "vector surface density" remains unaltered as the area between any planes P1 and P2 is the same for the sphere as for the cylinder.

The x components of the new vectors equal individually and in total, the x components of the original free path vectors and are now evenly distributed in length along the surface of the cylinder.

The mean length is $\frac{1}{2}$ the corresponding mean free path and the mean square $\frac{1}{3}$ the free path mean square. This is true for all groups; hence:

$$\lambda_{x-}=\lambda_{x+}=\lambda/2,$$
$$s_x^2=\tfrac{1}{3}\,2\lambda^2$$

For the positive and negative components together

$$\lambda_x=0 \qquad s_x^2=\tfrac{1}{3}\,2\lambda^2$$

and similarly for the corresponding velocity vectors.

Uniform Flux

The neutron flux at any point is defined as $\phi=\Sigma n_j v_j$, where n_j is the number of neutrons per c.c. having velocity v_j.

In a reactor the flux will vary from point to point. In considering the current at any point it is convenient to describe the flux in the neighbourhood of the point in terms of the mean value ϕ and the flux gradient $d\phi/dx$ and consider their separate contributions to the current.

In a uniform flux because of the spherical symmetry the number of neutrons with positive x components is $n_j/2$ and the magnitude of the mean component is $v_j/2$ as explained above.

The magnitude of the positive and negative neutron currents are:

$$J_+=J_-=\tfrac{1}{2}n_j\tfrac{1}{2}v_j=\tfrac{1}{4}\Sigma n_j v_j=\phi/4 \quad . \quad . \quad . \quad . \quad (1)$$

Neutron Movements

After a number of collisions N the mean distance travelled by the neutrons in the x direction is:

$$\bar{x}=\Sigma\lambda_x=\Sigma 0=0$$

The mean square value is

$$\bar{x}^2=\Sigma s_x^2=\Sigma 2\ \lambda^2/3$$

For fast neutrons during the slowing down period λ is in general different for each velocity range and for the average neutron

$$\Sigma 2\ \lambda^2/3=6L_{sx}^2$$

where L_{sx} is the x component of the slowing down length

$$L_s^2=\Sigma\ \lambda^2/3$$

The factor 6 is introduced into the definition of L_{sx} to simplify equations introduced later.

For thermal neutrons from thermalization to capture

$$\Sigma 2\ \lambda^2/3=N2\ \lambda^2/3=6L_x^2$$

where L_x is the x component of the diffusion length

$$L^2=N\ \lambda^2/3$$

There is only a small probability of absorption as a fast neutron. At thermal energies the mean line of flight distance travelled before an absorption collision is $1/\Sigma_a$ this being a zig-zag path with intermediate scattering collisions every λ. The number of scattering collisions is thus:

$$N=1/\Sigma_a\lambda$$

and

$$L^2=\lambda/3\Sigma_a=1/3\Sigma_a\Sigma_s$$

For both periods taken together

$$\Sigma 2\ \lambda^2/3=\Sigma 2\ \lambda_s^2/3+\Sigma 2\ \lambda_{th}^2/3$$
$$\therefore L_{sx}^2+L_x^2=M_x^2$$

where M_x is the x component of the migration length

$$M^2=L_s^2+L^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The values L_s, L, M and their components are standard deviations[1] of lengths whose mean is zero (because of spherical symmetry) and hence they are in themselves a measure of the arithmetic displacement of the neutrons although not in general the mean value.

Neutron Drifts

Symmetrical flux distributions produce no net current. In a flux gradient the neutrons arriving from one direction exceed those arriving from the opposite and a current results. Suppose a uniform gradient exists at $t=0$. At some time t, the total number of neutrons which have crossed the origin in the positive direction may be divided into groups all the members of a group having travelled equal distances but originating and terminating in different layers. If the distance travelled is l all must originate within this distance of the origin.

If the neutron density at the origin is taken as zero the neutrons from which this group derived total:

$$T=\int_0^l n\,dx$$

But

$$n=x(dn/dx)_0$$

so that

$$T=\int_0^l x(dn/dx)_0\,dx=(dn/dx)_0\,l^2/2$$

A proportion $p/2$ of each layer travel distance l as an equal number move in the opposite direction. Hence the number passing the origin in this group is:

$$(p/2)\,(dn/dx)_0\,l^2/2$$

For all groups the total is

$$1/4(dn/dx)_0\,\Sigma pl^2=1/4(dn/dx)_0 s_x^2$$

But in time t, the line of flight distance travelled by neutrons of velocity V is Vt and the number of collisions undergone by each is on average $N=Vt/\lambda$.

Thus

$$s_x^2=Vt\,.\,2\lambda^2/3\lambda$$

The number of neutrons is thus:

$$\frac{2Vt\lambda}{3}\,.\,(dn/dx)_0/4$$

and considering unit time the current is in excess of that from a constant flux by:

$$J=(d\phi/dx)_0\,.\,\lambda/6$$

The current in the reverse direction is less than that from a constant flux by the same amount. The difference is the net current

$$J=(d\phi/dx)_0\,.\,\lambda/3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(The x axis is here supposed to be in the direction of maximum flux gradient or the current is only a component of the total.)

Superimposing these currents on those for uniform flux gives for the total currents in each direction:

$$J_+=\phi/4-(d\phi/dx)_0\,\lambda/6$$

and

$$J_-=\phi/4+(d\phi/dx)_0\,\lambda/6$$

Reactors Unbuckled

The notions of a current and flux are used to describe the behaviour of neutrons in a reactor. It is proposed now to emphasize the close analogy between these quantities and electrical current and potential respectively.

The analogy may very naturally be extended to resistance here called NOHMS, a contraction of Neutron Ohms and together with the idea of a "Natural length" (for

reflectors) or " Pitch " (for core material) leads to a very understandable presentation.

In a homogeneous diffusing medium the absorption current is:

$$J=\phi\Sigma_a \text{ per unit volume.}$$

An absorption or shunt resistance may be defined as

$$s=\phi/J_a=1/\Sigma_a$$

The diffusion current density is from equation (3)

$$J_d=\frac{\lambda}{3}\,\text{grad}\,\phi$$

$$\left(\text{c.f. Ohm's Law}\ \frac{I}{A}=\frac{1}{R}\,\text{grad}\,V\right)$$

A diffusion or series resistance may be defined as

$$r=\text{grad}\,\phi/J_d=3/\lambda$$

In a volume of 1 cm^2 section and length $\sqrt{(s/r)}$ the series resistance is $r\sqrt{(s/r)}=\sqrt{(sr)}$.

The shunt resistance $s/\sqrt{(s/r)}=\sqrt{(sr)}$ also.

The specific resistance of the diffusion medium is

$$Z=\sqrt{(sr)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The various resistances mentioned are, in fact, more a property of the reactor than either the neutron flux or current for while at any point in the reactor these will vary with the power level at which the reactor is run, their ratio, the resistance, is constant.

The natural length is $L_n=\sqrt{s/r}=\sqrt{\lambda/3\Sigma_a}=L \quad . \quad . \quad . \quad (5)$

The natural length may be regarded as a unit of scale to which all significant dimensions of the material concerned are proportional.

For some possible moderators, values of L, M and Z and the values of L_s, Σ_a and λ from which they are derived are shown in the table below.

Moderator	Density g/c.c.	Σ_a cm^{-1}	λ cm	M cm	L cm	L_s cm	Z nohms
H_2O ..	1.0	0.017	0.426	6.4	2.88	5.7	20.2
D_2O ..	1.1	0.00008	2.40	101.0	100.0	11.0	125.0
Be	1.84	0.0013	2.10	25.6	23.6	10.0	33.2
Graphite ..	1.62	0.00036	2.71	53.6	50.2	18.8	55.7

In the core area it would be more accurate to use a Z calculated from M rather than L—but better still to use multigroup theory.

In a core material there is an excess of neutron production over absorption, i.e., the shunt current is negative and a quantity corresponding to s may be defined numerically as:

$$g=1/\Sigma_a\Delta k=s/\Delta k$$

Hence corresponding to L is a Pitch

$$P=\sqrt{(g/r)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

(buckling$=1/P^2$ was perhaps the worst thing that ever happened to Reactor Physics)

and corresponding to Z is

$$Y=\sqrt{(gr)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The significance of the Natural length, Pitch and Specific Resistance may be further demonstrated by transforming the diffusion equations for passive and generating mediums, i.e.

$$D\nabla^2\phi-\Sigma_a\phi=0 \text{ and } D\nabla^2\phi+\Sigma_a\Delta k\phi=0$$

according to the equations

$$x^1=x/L,\ y^1=y/L,\ z^1=z/L \text{ or } x^1=x/P,\ y^1=y/P,\ z^1=z/P$$

resulting in

$$\nabla^2\phi-\phi=0 \text{ and } \nabla^2\phi+\phi=0$$

Solutions of these equations depend only on geometry (not on material properties which are contained in the Natural Length or Pitch which are the units of length for their respective equations).

Neutron Leakage

In a finite system sustaining a chain reaction a proportion of the neutrons are lost by leakage from the system and the reproduction constant k is in excess of unity by a corresponding amount, i.e.

$$k=1+dk=1+dk_1+dk_2+\ldots.+dk_{th}$$

where the numerical subscripts indicate leakage of neutrons from the various energy bands during the slowing down process and " th " indicates leakage at thermal energies.

If a core of Pitch P has a natural length L when fission is suppressed then the proportion of neutrons leaking out of the system at thermal energies may be written as $dk_{th}=(L/P)^2$ or in terms of the specific resistances

$$dk_{th}=(Z/Y)^2$$

The non-leakage factor for thermal neutrons is

$$\frac{1}{1+dk_{th}}=\frac{1}{1+(L/P)^2} \text{ or } \frac{1}{1+(Z/Y)^2} \quad . \quad . \quad . \quad (8)$$

The fast neutron groups and the thermal neutron group must to a close approximation have the same natural length and pitch since the fission neutrons are created where the thermal neutrons are absorbed in fission reactions.

Similarly the thermal neutrons at a given point are produced from the fission neutrons at that point or within a migration distance from it. With the proviso that the flux gradient is approximately linear over this distance a deficiency of neutrons arriving from one side will be balanced by an excess from the other. (This implies that the core is many migration lengths in size.)

For each group (m) of fast neutrons the non-leakage factor is

$$\frac{1}{1+dk_m}=\frac{1}{1+(L_m/P)^2}$$

or for all fast groups together

$$\frac{1}{1+dk_f}=\Pi\frac{1}{1+(L_m/P)^2}$$

An upper limit is defined by

$$\frac{1}{1+dk}<\frac{1}{1+(\Sigma L_m/P)^2}=\frac{1}{1+(L_s/P)^2}$$

A lower and perhaps closer limit is

$$\frac{1}{1+dk_f}\simeq\frac{1}{\exp{(\Sigma L_m^2/P^2)}}=\exp-(L_s/P)^2 \quad . \quad . \quad . \quad (9)$$

as may be seen by comparing the expansions of the product Π with those of the centre term above.

The combined non-leakage factor is the product of the fast and thermal non-leakage factors, i.e.

$$\frac{1}{1+dk}=\frac{\exp-(L_s/P)^2}{1+(L/P)^2}\simeq\frac{1}{(1+L^2/P^2)\,(1+L_s^2/P^2)}$$

$$\simeq\frac{1}{1+(L^2+L_s^2)/P^2}=\frac{1}{1+(M/P)^2}$$

When the reproduction factor is unity, the core will just maintain the magnitude of any neutron population, i.e.

$$\frac{k\,.\,\exp-(L_s/P)^2}{1+(L/P)^2}=1 \quad . \quad . \quad . \quad . \quad . \quad (10)$$

This is a condition for criticality, relating the material properties to the leakage.

Neutron Flux, Current and Resistance in Reflector

In order to display the principles as clearly as possible the simplest geometry is used as an example, i.e. that of an infinite slab reactor. The complete reactor will consist of an assembly of core material, usually surrounded by a

layer of reflector material. This, like the moderator, will impede the diffusion and leakage of neutrons, and is required to have a high Z value. Taking the resistances as characterizing the reactor conditions, from point to point, the relationships of one volume element to the next reduces to the solution of a resistance network.

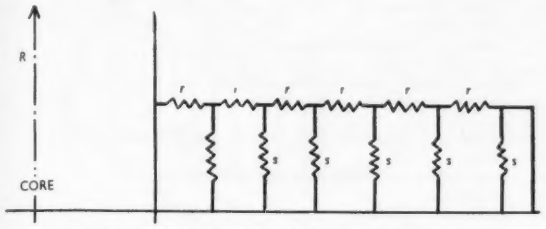


Fig. 2.—Equivalent circuit for the reflector.

The series and shunt resistances simulating the reflector characteristics are shown in Fig. 2. The electrical analogy being perhaps a d.c. power circuit, with series resistance in the conductor representing diffusion resistance and shunt resistance through the insulation representing absorption. At any point the change in apparent resistance in moving a small distance dx may be found thus

$$R=\phi/I \quad dR=d\phi/I-\phi dI/I^2$$

But $$d\phi=Ir\,dx \text{ and } dI=\frac{\phi}{s/dx}$$

$$\therefore \frac{dR}{(1-R^2/rs)}=r\,dx$$

One solution is

$$\sqrt{(rs)}\tanh^{-1}(R/\sqrt{rs})=xr$$

$$R=\sqrt{(rs)}\tanh\,(x/\sqrt{s/r})$$

$$R=Z\tanh\,(x/L) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Alternatively

$$R=Z\coth\,(x/L)$$

The shape of these curves is shown in Fig. 3, and it may be observed that starting from a value above or below Z the apparent resistance will change with distance, in both cases approaching an asymptotic value of Z, some typical values of which are given in the table (p. 172). Since the reactor surface approximates to a short circuit (but see eqn. 15), these values are the maxima which the various reflectors can offer to neutron leakage in the geometry under consideration—for other geometries the relative values will be unaltered but there will not in general be a single asymptotic value.

There is little increase in the apparent resistance for values

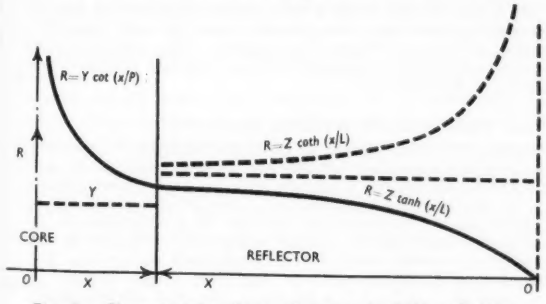


Fig. 3.—Characteristic shape of curves in both reflector and core.

of $x>2L$, i.e. there is little gain in making the reflector thickness greater than this value.

The functions ϕ and I (see Fig. 4) which satisfy the relations

$$R=\phi/I=Z\tanh\,(x/L)$$

and $$rI=-d\phi/dx$$

are $$\phi=ZI\sinh\,(x/L) \text{ and } I=I\cosh\,(x/L) \quad . \quad . \quad (12)$$

Neutron Flux, Current and Nohmage in Core

Corresponding to the reflector case is

$$R=\sqrt{(-gr)}\coth\,(x/\sqrt{-g/r})$$

$$=jY\coth\,(-jx/p)$$

$$=Y\cot\,(x/P) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

The alternative solution

$$R=Y\tan\,(x/P)$$

is not required for the geometry chosen and only the former is shown in Fig. 4.

The functions ϕ and I satisfying the relations

$$R=\phi/I=Y\cot\,(x/P) \text{ and } rI=-d\phi/dx$$

are $$\phi=\phi_0\cos\,(x/P) \text{ and } I=(\phi_0/Y)\sin\,(x/P) \quad . \quad . \quad (14)$$

Surface Resistance and Extrapolated Distance

The external surface of the reactor may be considered to have a resistance. Assuming that no neutron current enters the surface from outside the reactor and the emerg-

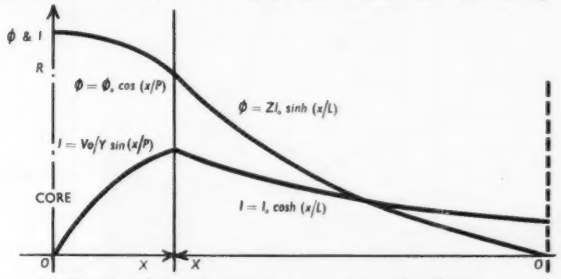


Fig. 4.—Flux and current across core and reflector.

ing neutrons to have velocity vectors uniformly distributed as in the paragraph on Uniform Flux:

the flux is then NV.

The average value of the vectors in the direction normal to the surfaces is $\phi_s/2$ and the current thus $NV/2$.

Hence $R=\phi_s/I=2$ Nohms or 2.13 Nohms . . . . (15)

according to transport theory modifications[3] for the flux is not now spherically symmetrical.

Resistance is non-dimensional, representing the summated random neutron velocities as a multiple of the summated directed velocities. The figure 2 of equation 15 is that in the term $V_j/2$ in the paragraph on Uniform Flux.

It is convenient to use the extrapolated dimensions of a reactor where the resistance is zero—see Fig. 5. This may be supposed to occur where the flux curve continued at its surface gradient meets the x axis.

Now $$I=(\lambda/3)\text{ grad }\phi \text{ and } I=\phi_s/2.13$$

$$\Lambda\text{ grad }\phi=\phi_s, \Lambda=\phi_s/\text{grad }\phi=2.13\lambda/3=0.71\lambda \quad . \quad . \quad (16)$$

Critical Size

For a given value of P the boundary of the reactor is determined by equating the core resistance Y to 2.13. The extrapolated boundary is determined by equating the core resistance to zero. The latter may enable a convenient relation to be established between the Pitch and extrapolated dimension.

For the geometry of the infinite slab reactor

$$R=Y\cot\,(D_e/P)=0.$$

As $$Y=0 \text{ then } \cot\,(D_e/P)=0 \text{ or } \frac{D_e}{P}=\frac{\pi}{2},\ D_e=\frac{\pi}{2}P \quad . \quad (17)$$

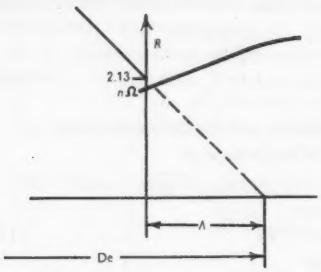


Fig. 5.—Extrapolated dimensions of a reactor where the resistance is zero.

This is a condition for criticality relating material properties to reactor dimensions.

Conversely for a required D_e this equation determines P and hence k.

One or more reflectors may be added to the core to reduce neutron leakage. At a surface in the reactor where the material properties change the flux and current passing through a given area of the surface must be equal immediately on either side of the surface. The ratio $\phi/I=R$ must also

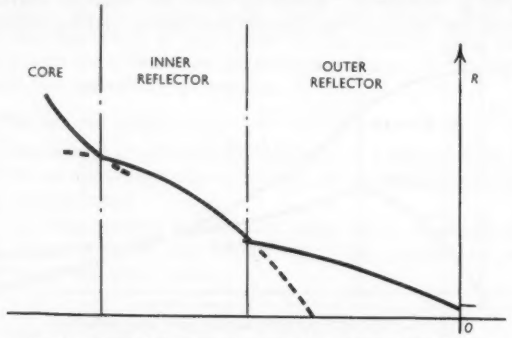


Fig. 6.—Typical resistance curve for a reactor with two reflectors of differing nuclear properties.

be unchanged. With one reflector layer of thickness T the core and reflector resistance are equal when

$$Y \cot (D/P)=Z \tanh (T/L) \quad . \quad . \quad . \quad . \quad (18)$$

This trancedental equation defines a value of D smaller than D_e of equation (17).

List of Symbols

C	isotope concentration
D	distance or position—or Drag
f	suffix for fast neutron group
G	Gain
g	generating negative resistance
I	current
i	current variation—or term marker
J	current density
j	term marker
k	constant—reproduction constant
L	particular length—or inductance
l	general length—or neutron lifetime
M	migration length
m	mean value
N	number of collisions in particular—or neutron density
P	pitch
p	probability—resonance escape probability
R	resistance
r	diffusion resistance
S	signal
s	standard deviation—or absorption resistance
t	time
V	average neutron velocity
v	neutron velocity
x	variable
Y	characteristic generation resistance
y	variable
z	variable
Σ	sum of—or cross-section
δ	perturbation or finite change sign
Λ	extrapolation distance
λ	mean free path
β	proportion of delayed neutrons
τ	decay constant
ϕ	flux
Δ	finite difference sign
ϱ	reactivity

If there are two reflectors, the graph of resistance is as shown in Fig. 6, the outer being equivalent to that thickness of the inner reflector that would provide the same resistance at the reflector/reflector boundary. This arrangement might use graphite to economize heavy water (the inner reflector) which can achieve better core savings than graphite as its Z value is higher.

REFERENCES

1. Aitken, A. C. "Statistical Mathematics." (Oliver and Boyd.)
2. Hicks, D. A.E.R.E. Report No. R/R 2418.
3. Glasstone and Edlund. "Elements of Nuclear Reactor Theory." (Macmillan.)

La Physique Nucléaire pour l'Ingénieur-Electricien.

Bien que la façon traditionnelle d'aborder la physique des réacteurs soit maintenant bien connue, l'approche peut embrouiller à un certain point l'ingénieur-électricien traditionnel qui sera, toutefois, au courant des expressions mathématiques qui sont apparentées de près à celles qu'il rencontre lors de la description du comportement des neutrons. En partant des théories bien connues de la probabilité, l'auteur développe des expressions qui décrivent le comportement des réacteurs, ce qui élimine le besoin du "buckling" et introduit des concepts électriquement équivalents, tels que le "nohmage" (la résistance neutronique), la longueur naturelle et le pas.

Dans cette première partie d'un article en deux parties, les expressions essentielles sont développées et la nouvelle nomenclature est introduite. Le second article établira des analogies particulières entre les circuits de réacteurs et les circuits électriques.

Atomphysik für den Elektro-Ingenieur

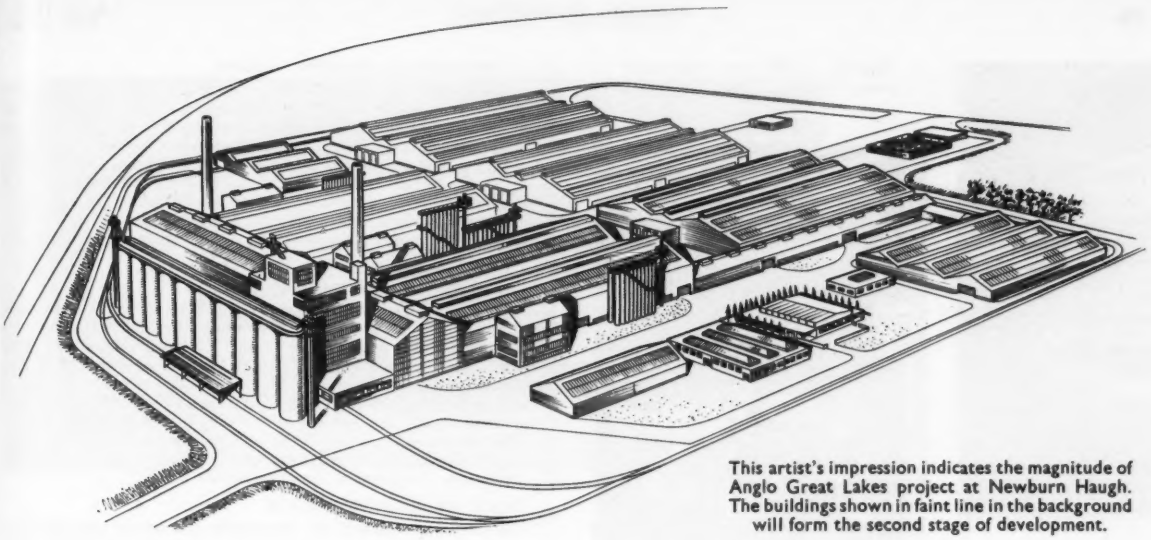
Wenn auch die klassische Betrachtungsweise der Reaktoren-Physik jetzt bereits Gemeingut geworden ist, so ist sie doch etwas fremd für den traditionell denkenden Elektro-Ingenieur, der aber mit mathematischen Ausdrücken vertraut sein wird, die denjenigen sehr nahe kommen, die zur Beschreibung des Verhaltens von Neutronen dienen. Der Verfasser geht von allgemein bekannten Wahrscheinlichkeits-Theorien aus und entwickelt Ausdrücke, die das Verhalten eines Reaktors beschreiben, bei dem der Zwang zur "Verformung" ("buckling") wegfällt, und er führt elektrische Equivalente ein, wie z.B. "Nohmscher" Widerstand (Neutronen-Widerstand), natürliche Länge und Steigungswinkel.

Im ersten Teil des in zwei Teilen erscheinenden Artikels werden die wichtigeren Ausdrücke entwickelt, und es wird eine Einführung in die neue Terminologie gegeben. Der zweite Artikel wird dann spezifische Analogien aufzeigen zwischen Reaktorkreisläufen und Stromkreisen.

Física Nuclear para el Ingeniero Eléctrico.

Aunque el método clásico de tratar con la física de reactores es ahora bien conocido, este método es algo desconcertante para el ingeniero electricista, el que, sin embargo, estará familiarizado con las expresiones matemáticas que tienen estrecha analogía con aquellas que se encuentran en describir el comportamiento de neutrones. Partiendo de los bien conocidos principios de las teorías de probabilidad, el autor evoluciona expresiones que describen el comportamiento de reactores, lo que elimina la necesidad de "buckling" e introduce conceptos eléctricamente equivalentes, tales como "nohmage" (resistencia neutrónica), largo natural y paso.

En la primera parté de un artículo en dos partes, se desarrollan expresiones esenciales y se introduce la nueva terminología. El segundo artículo desenvolverá analogías específicas entre los circuitos de reactores y los circuitos eléctricos.



This artist's impression indicates the magnitude of Anglo Great Lakes project at Newburn Haugh. The buildings shown in faint line in the background will form the second stage of development.

Nuclear Graphite Production

A new factory for the manufacture of nuclear and other grades of graphite is now in operation at Newburn Haugh, Newcastle upon Tyne.

(Right) Delivery of petroleum coke at Newburn Haugh.

TO erect a £6 million factory and produce nuclear graphite 17 months after work started on the site is an outstanding achievement, and Anglo Great Lakes Corporation have every reason to be proud of their accomplishment. The company's new factory at Newburn Haugh, Newcastle, owes its existence in no small measure to the tenacity of the late Sir Claude Gibb, chairman of NPPC. Realizing that the CEGB programme for nuclear stations announced in 1956 would require increasing quantities of nuclear graphite, Sir Claude won AEA approval for a project to produce reactor-quality graphite in a factory specially built for that purpose.

Whilst negotiations were taking place it was learnt that the Great Lakes Carbon Corporation of America wanted to establish a factory in Europe. The company was prepared to make its experience available in helping to set up a works, which would not only meet the requirements for nuclear graphite, but which would, at the same time, make graphite of commercial quality such as is required by steel works for electric furnace electrodes and by chemical works for anodes. The basis of the philosophy was sound: in the event of graphite in future years being superseded by other moderators, then the entire factory would be well established to meet the growing demand for commercial graphite.

Finding a site of sufficient size and with adequate electrical power, water, road and rail access was a problem in itself. The most suitable location in the Newcastle area was already reserved by CEGB for possible extension, to Stella North. Fortunately, the Board agreed to release the site and, following visits to the Great Lakes' factories in the U.S.A., plans were prepared for construction of a factory.

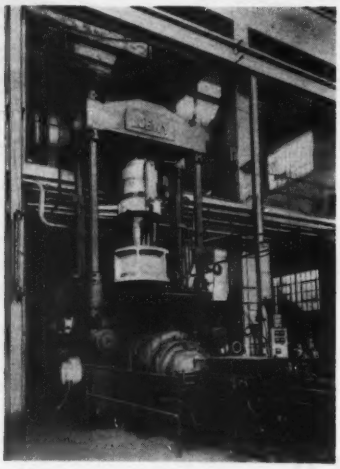
On January 23, 1957, the first bulldozer arrived on the 94-acre site. Without waiting for a sod cutting ceremony, construction continued at a very rapid rate, so that by the end of that year the major part of the equipment had been installed in the completed buildings. On June 28, 1958, samples from a furnace load of 50 tons of completed graphite blocks, tested in GLEEP at Harwell, were reported by the AEA to be of acceptable quality as grade "A" reactor graphite.

Construction of the factory in such an amazingly short period can only be attributed to the excellent collaboration between Anglo Great Lakes personnel seconded from the American company and the British main contractors. Most of the work was in fact handled by constituent companies in the NPPC group—among them C. A. Parsons (overall design and supervision), Sir Robert McAlpine and Sons (civil engineering), Alex Findlay (structural steelwork), together with formidable contributions from Clarke Chapman and A. Reyrolle.

An unusual feature of the site is that it consists of sand and gravel to a depth of 130 ft. To carry the heaviest loads extensive use was made of friction piles and foundations had to be designed to spread the load. In excavating pits, for example, two of the largest being 140 ft by 140 ft by 16 ft deep, additional space was necessary to allow for the natural slope of sand. Four heavily reinforced concrete tanks were built—each designed to hold a batch of

(Above) Panel for fine control of blending coke particles, flour and coal tar pitch.

(Below) 2,000-ton extrusion press with 850-ton tamping unit.



seven muffle furnaces required to bake the extruded carbon blocks. Over three million fire bricks and 1,000 tons of refractory cement were used in their construction.

For direct access from Scotswood Road, it was necessary to construct a bridge across Lemington Gut, the partly filled-in bed of the Old River Tyne loop. This bridge, which has the elegant lines of modern light-weight construction, is built of pre-stressed concrete with three spans, the centre span being 70 ft.

Nuclear quality graphite is made by mixing crushed petroleum coke with hot pitch to form a paste which can be extruded through dies into square-shaped blocks. The blocks are first baked to form a hard carbon which is then impregnated with pitch to raise its density and finally changed to graphite by resistance heating in graphitizing furnaces.

A special feature in the production of nuclear graphite is the maintenance of exceptionally clean conditions at all stages in manufacture. The raw materials are chosen for their freedom from contamination of elements known to absorb neutrons. Regular vacuum cleaning of the entire factory is essential and materials must be at all times under cover. Clean overalls must be provided for all personnel.

Some idea of the need for these precautions may be gathered from the fact that reliable tests have been found to be impossible if the laboratory analyst uses the wrong type of hair cream. Contamination is measured in fractions of one part in a million of the sample.

In its first stage of development, the plant is designed for an annual production of up to 10,000 tons of moderator bricks for nuclear reactors and 5,000 tons of graphite for electrodes and anodes. Nuclear graphite is being produced at present for Bradwell power station in blocks which are 8¼ in. by 8¼ in. by 66 in. long. After graphitization these blocks are cut in half prior to dispatch.

Commercial graphite will be produced as cylindrical electrodes up to 30 in. in diameter and 7 to 8 ft long. The blocks will subsequently pass through specially designed shuttle-type machines which drill and thread the electrodes to take unions for continuous feeding in electric furnaces.

For nuclear graphite, the raw material is calcined petroleum coke of high purity brought from an oil refinery

La Production de Graphite Nucléaire

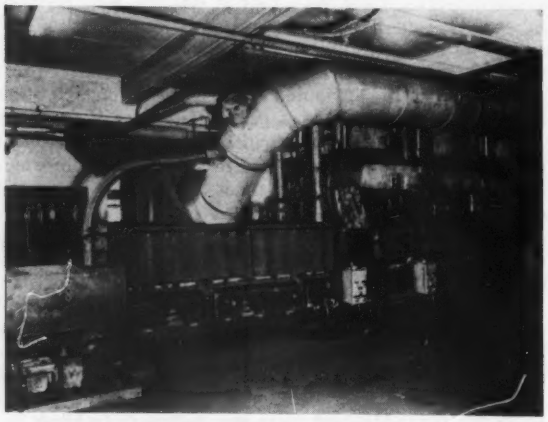
Du graphite de qualité nucléaire est maintenant en production dans une nouvelle usine de Newcastle. Cette installation de 6 millions de livres, entreprise anglo-américaine, est sous la direction de l'Anglo Great Lakes Corporation. On s'attend aux débuts à une production annuelle de 10.000 tonnes de graphite nucléaire et de 5.000 tonnes de graphite commercial. La totalité du rendement de graphite nucléaire est achetée par l'United Kingdom Atomic Energy Authority pour la revente aux sociétés construisant des centrales d'énergie nucléaire modérées au graphite.

Produktion von Nuklearem Graphit

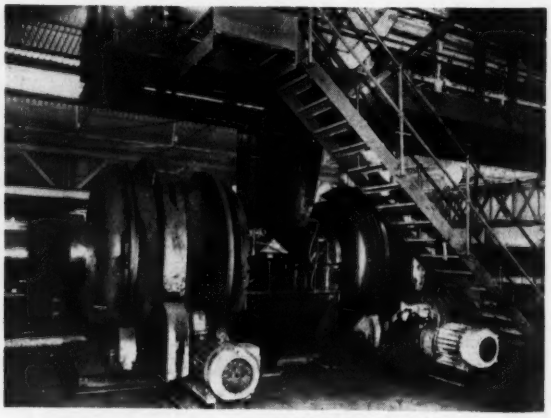
Nuklearer Graphit wird jetzt in einem neuen Werk in Newcastle produziert. Das Werk, das einen Wert von £6.000.000 hat, ist ein gemeinsames englisch-amerikanisches Unternehmen und steht unter der Verwaltung der Great Lakes Corporation. Für den Anfang erwartet man eine jährliche Produktion von 10.000 t nuklearem Graphit und 5.000 t handelsüblichem Graphit. Die gesamte Produktion von nuklearem Graphit wird von der United Kingdom Atomic Energy Authority übernommen, die den Graphit an die Gesellschaften weiterverkauft, die die mit Graphit als Moderator betriebenen Atomkraftwerke bauen.

Producción de Grafito Nuclear

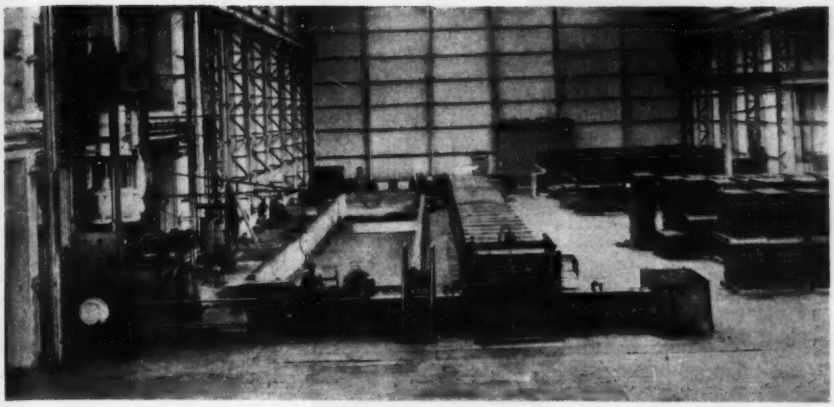
Una nueva fábrica en Newcastle está ahora produciendo grafito de calidad nuclear. Esta empresa es angloamericana, y el la planta cuyo costo asciende a £6.000.000, es operada por la Anglo Great Lakes Corporation. Inicialmente se anticipa una producción anual de grafito nuclear de 10.000 toneladas a la par con 5.000 toneladas de grafito comercial. La producción total de grafito nuclear va a ser comprada por la Autoridad de Energia Atómica del Reino Unido para ser revendida a las compañías constructoras de centrales de fuerza nuclear moderadas con grafito.



To ensure a thorough mix steam jacketed paddle mixers are used.



Before extrusion the mix is cooled by air in these rotary drums.



After extrusion the green carbon is automatically sheared into 66-in. long blocks before being passed to the cooling bay.

in a coaster specially chartered by the AEA. The coke, which must be kept scrupulously free from contamination or moisture, is discharged during fine weather at a 300 ft quay equipped with a 5-ton level luffing travelling crane. The coke is discharged by grab into a hopper attached to the crane, thence by covered belt conveyors to one of 10 concrete silos, each capable of holding 500 tons.

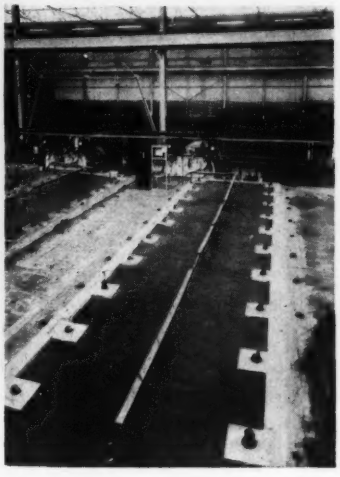
The process begins by crushing part of the coke into a series of different particle sizes, obtained by passing over vibrating screens, and also by milling the remainder to a fine flour. The particles, flour and crushed coal tar pitch, also of high purity, are then stored in separate hoppers near the top of a six-storey building. A unique weighing and handling equipment transfers pre-selected weighments from the hoppers pneumatically to a series of steam-jacketed paddle mixers. Great care is taken to ensure accurate blending. Upon the success of mixing depends the final strengtth of the graphite and freedom from flaws and cracks.

After mixing, the temperature of the hot paste is gradually dropped in an air cooler until it is ready for extrusion. It then falls into the main cylinder of a 2,000-ton extrusion press, situated on the ground floor. This trunnion-mounted press cylinder is first rotated into an upright position to tamp the mixture by a vertical ram. This unit has an effective tamping pressure of approximately 850 tons. The cylinder then rotates into a horizontal position for the 3 ft diameter main ram to extrude the mixture through electrically heated reducers and dies. As the square shape leaves the die, at a temperature of 100°C, it is cut to length, as it moves, by shears and then automatically transferred to a cooling belt, at the end of which each block is checked for density and a visual inspection of all its faces. It is also stamped with a code number.

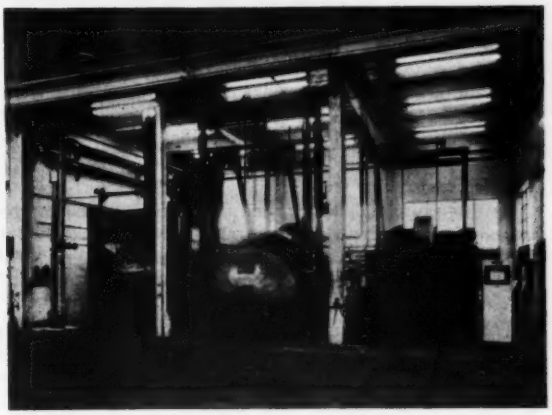
Exceptionally fast steel-works type cranes ensure rapid handling throughout the works. Between the extrusion and baking bays these cranes are at two levels to enable groups of carbon blocks to be transferred ready for subsequent unloading into the baking furnaces. Each of these furnaces is designed to take 100 tons of blocks, tightly packed in coke, up to a temperature approaching 1,000°C.

They are indirectly fired, using heavy fuel oil which is burnt in a combustion chamber. The hot gases are recirculated around each of ten cells, suitably controlled to ensure uniform temperature. After this baking process, which takes about two weeks, the carbon blocks are removed whilst still hot on to a slowly travelling cooling conveyor. This device ensures that the blocks are cooled before being passed automatically, one at a time, through a wire brushing machine to remove adhering packing coke. Measurements of density, resistance and a visual inspection take place as the blocks pass over conveyors to be regrouped on to pallets for pitch impregnation.

To speed the impregnation process the blocks are pre-heated: quick transfer in and out of the vacuum pressure autoclave is assisted by a novel type of boltless door arranged with " U " ring pressure sealing. A second baking process, also taking two weeks, changes the impregnated

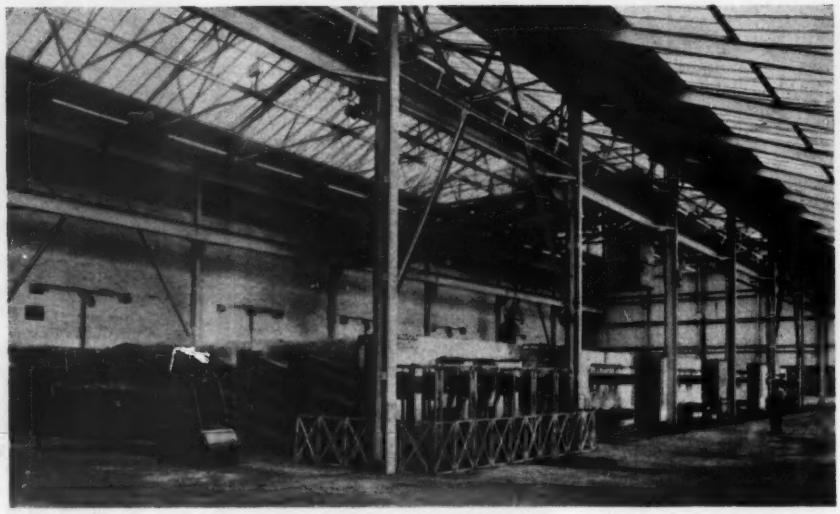


In the oil-fired baking furnaces, the carbon blocks are subjected to a temperature of up to 1,000°C.



Impregnation of the block is effected in this vacuum vessel (centre). Prior to impregnation blocks are pre-heated.

K



(Left) Graphitizing furnace.

pitch in the blocks to coke in the same way as the first baking cycle. The blocks are then cooled, brushed, tested and passed by conveyor into the graphitizing bay.

Graphitization is completed when the baked carbon blocks are heated in resistance furnaces to 2,800°C, at which temperature they become crystalline. This heating and cooling cycle takes approximately two weeks. Each furnace takes 30 to 40 tons of blocks placed in tiers with crushed petroleum coke packed between and around the charge and an insulating envelope of sand and coke mixture over it, acting as a cover to form a muffle furnace.

Separate power transformers are connected to each group of furnaces by an aluminium busbar designed to carry a high current for the initial furnace heating-up period and a separate busbar carrying a higher current for full heating. Specially designed switches mounted on cranes traverse the pressurized busbar chamber to make off-load connection between the busbar and the furnaces on either side of the busbar. For this a 10-ton thrust is hydraulically applied to make contact between the very heavy interleaved busbar and the furnace take-off connection.

Duplicate 132 kV overhead lines supply power direct from Stella North substation to two 30 MVA transformers, which reduce the voltage to 11 kV. At this voltage power is taken from a switching station to each graphitizing furnace transformer and from a ring main to substations supplying power to equipment, lighting and floor heating. The controls for the graphitizing operation are grouped together in an adjacent control room.

The ultimate density of the graphite blocks is dependent upon the number of times that the block is reimpregnated and passed through the graphitizing stage. When the required density for nuclear applications has been obtained in this way the blocks are slowly cooled before being weighed and cut to size.

At this point, the blocks are inspected by AEA inspectors. Blocks intended for use at Bradwell are passed by the AEA inspectors to the graphite machine shop established by A. Reyrolle and Co. and located adjacent to the Anglo Great Lakes factory.

The excellent facilities for graphite production at Newburn Haugh are supplemented by a number of ancillary units. For example, a machine shop to produce commercial grade electrodes will shortly come into operation. The administration buildings also house a drawing office and a fully equipped experimental laboratory. Raw materials and process material can be quickly analysed and there is even a miniature pilot plant in which small quantities of graphite can be produced in a matter of days compared with two to three months in the main production line.

Although the number of staff at Newburn Haugh is small in comparison with the capital investment, care has been taken to provide a well-equipped canteen centre, a clinic and an extensive ablution centre. The latter is, of course, essential to ensure complete cleanliness at all stages of production.

PRINCIPAL CONTRACTORS

AUSTIN BEECH LTD.
Graphitizing coke conditioning plant.

BRITISH INSULATED CALLENDER'S CABLES LTD., Norfolk House, Norfolk Street, London, W.C.2.
Busbars, cables, etc.

CLARKE CHAPMAN LTD., Victoria Works, St. James's Road, Gateshead, Co. Durham.
Conveying equipment in association with Moxey Ltd., Birmingham; Richardson Scale Co. Ltd., Bulwell, Notts; John Thompson Industrial Construction Co. Ltd., London.

DALLOW LAMBERT LTD., Thurmaston, Leics.
Dust-control equipment.

ALEX FINDLAY AND CO. LTD., Motherwell, Lanarkshire.
Structural steelwork.

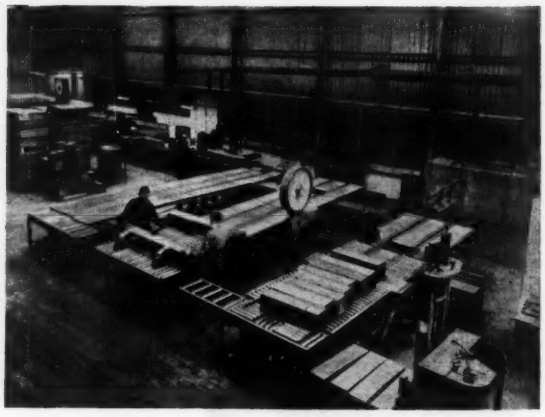
GENERAL ENGINEERING (RADCLIFFE) LTD., Radcliffe, Lancs.
Vacuum vessels.

SIR R. McALPINE AND SONS (NORTH EASTERN) LTD., Newcastle upon Tyne.
Civil engineering.

C. A. PARSONS AND CO. LTD., Heaton Works, Shields Road, Newcastle upon Tyne 6.
General supervision of contracts; transformers.

A. REYROLLE AND CO. LTD., Hebburn, Co. Durham.
Switchgear and control gear.

WALLSEND SLIPWAY AND ENGINEERING CO. LTD., Wallsend, Northumberland.
Oil firing.



After removal from the graphite furnace, blocks are slowly cooled prior to final inspection.

Technical Papers and Publications

Welding—A Sir Leonard Owen Paper

Welding and the Nuclear Power Programme, by Sir Leonard Owen, C.B.E., M.Sc., M.I.C.E., M.I.Mech.E., M.I.Chem.E.

The paper was presented to the Institute of Welding on March 12 and in the absence of the author was read by Dr. McIntosh, head of A.E.A., Culcheth Laboratories.

Welding is a joining technique indispensable in reactor construction and therefore has received close attention by the nuclear engineer in the recent past.

The paper is exclusively concerned with the conditions in, and the materials for, the building of nuclear power producers. Three types of reactor are discussed: the Calder Hall type, the Advanced Gas-cooled type and the Fast Fission Breeder type. The first is dealt with more extensively than the remaining two, because its performance and experimental results have an immediate bearing on present-day design and construction of civil installations. The second employs ceramic fuel, operates at higher temperatures and uses beryllium cans, thus introducing new fabrication problems. The third is still comparatively unexplored and may not become an industrial proposition before the 1970s but it is expected ultimately to produce electricity cheaper than any of the other reactor types at present known. It features new departures re design and construction materials, of considerable potential significance to the welding specialist.

In all three cases the discussion concentrates on two major part assemblies in nuclear plant, i.e., the can (fuel element) and the pressure vessel.

Calder Hall Type

The fuel cans are made from magnesium alloy (Magnox) and therefore brazing is excluded. The fuel (natural uranium) tends to grow and swell during operation of the reactor. Thus, the length of a fuel rod may increase by 3% and the overall dimensions of the individual charge by as much as 15%. In addition, the material of the can may show creep and stress concentrations in the joints, caused by uneven heat transfer and by the continuous neutron irradiation.

Welding of the can is effected by two processing steps, employing the inert-gas tungsten arc method. In the first operation a short arc is used producing a somewhat irregular weld and this is smoothed over in the second operation where a longer arc is used. The weldments are inspected prior to operational use of the can by means of the mass spectrometer leak testing method, normally employed in vacuum engineering. The probe gas is helium. The maximum permissible leakage is 1 clusec*, i.e., a leakage path of 1/10.000 inch is the upper limit for a "pass." It speaks for the quality of up-to-date welding techniques that out of 60,000 magnesium fuel cans tested, only 7 cans were rejected and of these only 4 on the ground of pin holes of excessive size.

Pressure vessel construction presents additional difficulties because, by necessity, the vessel has to be fabricated and inspected on site. As in the case of the cans, inspection must be carried out before the vessel is put to operational use; otherwise, inspection would have to be handled from a remote position. The specific danger to guard against here, is brittle fracture. Effective preventive action in the design or construction stage suffers from a lack of positively established data on the effects of operational conditions in a reactor on the transition temperatures of construction materials, in particular steel. Some information has been obtained by practical experiment, after placing specimens of various materials in different parts of a reactor plant.

It is now known that steel transition temperature, for instance, increases progressively with the length of the period of irradiation by neutrons but the actual transition temperature values applicable in the individual conditions are still largely a matter of estimating. An exact knowledge of the ductile-brittle transition temperature values would materially assist in counteracting potential formation of ductile (slow travelling) and brittle (fast travelling) cracks. Such cracks may originate from a minute area in the weld, such as a small sharp point, should it so happen that this point forms the centre of a stress concentration.

Inspection methods. The thickness of the plates normally used in modern pressure vessel construction is 3 in. and plates of this thickness can be satisfactorily inspected on site by radiography, enabling the detection of flaws of extremely small dimensions. In theory, an exposure should take about 20 min but, in practice, it normally takes longer (up to 2 hours) depending on the conditions on the building site. The use of cobalt-60 plant sources represents the latest development of apparatus facilitating inspection by means of gamma rays.

The trend is to increase the thickness of pressure vessel plates and this involves a search for new working principles which can be developed to yield a testing method as satisfactory for thicker plates as the radiographical method in the range up to 3 in. One such method suggested recently is based on the use of the linear accelerator and, in fact, units suitable for manipulation on site are in the development stage now. Another principle, thus far employed successfully in auxiliary tests, is the ultrasonic method of inspection. The latter has the advantage that the thickness of the plate inspected is immaterial and therefore this method can be expected to gain appreciably in importance in the future. Finally, the urgent need for the development of leak testing apparatus which facilitates the testing of large-size reactor plant, should be placed on record. The magnitude of the inspection task can be deduced from the fact that the Calder Hall type of reactor contains some 20 tons of weld material.

*1 clusec—0.01 lusec;
1 lusec—1 litre-micron/sec;
0.76 lusec—1 mm³/sec at N.T.P.

Advanced Gas-cooled Type

Cans. The governing factor controlling the fabrication and joining of cans employed in this reactor is the health hazard involved in processing beryllium. The accepted safety standard permits a beryllium vapour content of no more than 1/2,000,000 g in 1 cu m_3 of air. It follows that all fabrication has to be carried out in fully enclosed equipment. Two methods of welding are in use: fusion and pressure welding. In the case of the former an inert atmosphere of extreme purity is required and in the case of the latter the ambient temperature must be controlled with exceptional precision. There are edge, corner and butt welds which must be completely gas-tight with respect to the coolant (CO_2).

The pressure vessel is fitted with an internally located radiation shield which has the effect that the shell stress is appreciably reduced. Thus, pressure shell design is simplified.

Fast Fission Breeder Type

The cans in this reactor constitute double-walled assemblies. The inner tube is made of vanadium and the outer tube is made of niobium. Joining of the two tubes involves essentially one welding operation only, i.e., an annular butt weld, as the vanadium tube is assembled as a push fit to the end plugs. Details of the welding rig employed in this operation are shown in an illustration (not reproduced).

The coolant is liquid sodium. The cooling circuit, constructed throughout from stainless steel, has to be completely leak-proof and must be carefully inspected. Only butt welds are used. Testing of the circuit is carried out by three methods, applied in succession: a radiographical test, a halogen leak test and a nitrogen pressure test.

In his concluding remarks the author emphasizes that further reactor development is very largely dependent on correspondingly satisfactory developments in the field of inspection techniques. This applies in particular to the last mentioned two types of reactor which operate at higher temperatures than the Calder Hall type and involve the use of a great variety of new materials in their construction.

Asymmetrically Ring Reinforced Circular Hole in a Uniformly End-loaded Flat Plate with Reference to Pressure Vessel Design. By R. Hicks. (Paper presented to the Institution of Mechanical Engineers in December, 1958, for written discussion.)

General expressions are obtained for the stress distribution in an infinite flat plate end-loaded by equal principal stresses and containing a circular hole reinforced by a compact ring, the ring reinforcement being placed on one side of the plate only so that the other side of the plate remains flush. It is shown that the effect of an asymmetrically placed reinforcement is to induce in the plate and reinforcement bending stresses which are not negligible compared with the externally applied direct stress. Furthermore, from particular examples considered, it is found that reinforcements having practical dimensions can give rise to stress concentrations in the same order of magnitude as those in a similarly loaded plate containing an unreinforced hole. Thus, a reinforcement designed to satisfy B.S. 1500:1949 has a small compensating effect compared with a symmetrically placed reinforcement having the same cross-sectional area. For practical purposes, data have been obtained which enable the designer to determine quickly the stress distributions associated with reinforcements and plates having a reasonably representative range of dimensions.

The Design of Electro-mechanical Auxiliaries Directly Associated with Power-producing Reactors. By A. E. Harwood, P. Scott, and B. H. Stonehouse. (Paper presented to the Institution of Electrical Engineers in December, 1958.)

Novel problems are encountered in the design and construction of the electro-mechanical plant directly associated with the reactor in a base-load nuclear power station of the gas-cooled graphite-moderated natural uranium type. The reactor servicing machine in question is mounted above the biological shield and is used for (a) withdrawing and replacing the control rods, (b) insertion of fuel elements, (c) emergency extraction of fuel elements from the core and (d) lowering a television camera into the reactor. Suitable construction materials are discussed. Electrical insulators which are radiation resistant and can be classed as good are: all ceramics, mineral-filled phenolics, polystyrene, polythene; and as poor, all cellulose compounds and P.T.F.E. Finally the authors examine the features required by the operator for controlling the plant from a remote point.

Some Metallurgical Features of Nuclear Reactors. By H. M. Finniston. (Paper published under the auspices of the Joint Panel on Nuclear Marine Propulsion on March 3, 1959.)

The author examines up-to-date reactor engineering conditions from the angle of the potential use of nuclear reactors for ship propulsion. Fuel properties and behaviour are discussed as well as the various can materials used today and the fabrication problems involved. Finally, pressure vessel construction is discussed and, in that connection, welding problems are mentioned. A table follows, reproduced from the article, on the effect of neutron irradiation on the tensile properties of weld metals.

Tensile Results on Irradiated Carbon Steel Weldment
Strain rate 0.05 min^{-1}: irradiation temperature 95°C (203°F) (maximum)

Dose[1] n/cm² >1 MeV	Yield stress, 10^3 lb per in.²	U.T.S., 10^3 lb per in.²	Total elong. %
ASME SA 212 Base plate			
0	41·3	75·4	35
$1·7\times10^{19}$	91·6	98·0	11·6
10^{20}	108·5	115·8	7
E 7016 Weld Metal			
0	57·9	73·2	25·5
0	66·5	74·0	20·5
5×10^{18}	69·3	77·5	18·5
$1·7\times10^{19}$	108·7	*	8·0
10^{20}	115·0	*	7·5

* Load decreased continuously after initial yielding.

Purification of Hydrogen for Distillation: Part II. By W. H. Denton, B. Shaw, R. Gayler and P. Seager. (Paper delivered to the Spring Meeting of the Institution of Chemical Engineers on March 17, 1959.)

An experimental plant for studying the performance of plate-fin reversing heat exchangers is described. It was employed over the temperature range 300°-80°K for the purification of hydrogen. This is a major problem in the distillation of hydrogen for large-scale deuterium production. With carbon dioxide as impurity and a hydrogen flow rate of 600 ft^3/h, it is demonstrated that this type of heat exchanger overcomes the problem caused by the inherent supersaturation of impurities in hydrogen and the consequent transport of solid fog particles in the gas stream and accumulation of solid in the heat exchanger. This is attributed to the action of an interrupted or "multi-entry" fin geometry in providing good nucleation surfaces and in trapping any solid particles. Continuous records of the impurity concentration at various temperatures over the range of deposition confirm the absence of solid particles in the gas stream and provide a very clear demonstration of the basic principle of the reversing heat exchanger. In experiments of up to 72 hours duration with molar feed concentrations of up to 1%, the total solid accumulation is less than 2 p.p.m. of the molar feed. This is an acceptable figure for large-scale plant. It is also shown that this type of unit could handle higher concentrations.

The Extraction of Thorium. By J. H. Buddery, W. D. Jamrack and R. A. Wells. (Paper delivered to the Chemical Engng. Group, Society of Chemical Industry, on February 10, 1959.)

Nuclear grade thorium can be extracted economically from monazite sand, rock monazite, thorite or uranium ore residues. Various methods of opening the ores are feasible, based upon sodium hydroxide, concentrated sulphuric acid, dilute acids or chlorine. Intermediate purification methods involve oxalate precipitation, adsorption upon cellulose phosphate, basicity separation, precipitation of anhydrous thorium sulphate or complexing with alkyl phosphates or alkylamines. Final purification is by tributyl phosphate extraction before conversion to pure thorium oxide. Thorium metal is produced from the latter by reduction with calcium or by conversion to thorium tetrachloride and molten salt electrolysis.

NEW BOOKS

Atomterminologie (Dictionary of Atomic Terms in English, German, French and Italian). By Lore Lettenmeyer. (298 pp. Isar Verlag, Munich, Germany, DM. 24.80.) Sole distributors in the British Empire: Temple Press Limited.

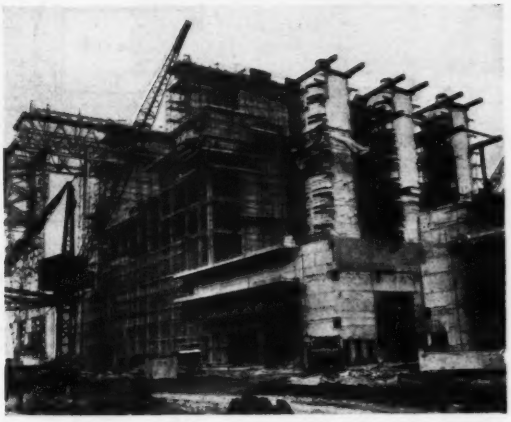
The absence so far of a German nuclear dictionary has been brought home especially in recent years by the expansion of the nuclear sciences in the Western European countries and the correspondingly high output of scientific and technical papers. For the specialized purpose of reading and translating nuclear papers hardly any of the existing dictionaries have been of much help. Most devote a disproportionate number of entries to terms found in general dictionaries, and thus inevitably waste the user's time. The new dictionary is completely free from this vice. No terms other than those wanted in its specialized field are included, and the entries are judiciously chosen so as to overlap to just the necessary extent with solid state physics and electronics.

The reviewer is normally against multiple dictionaries, though there are obviously reasons for producing them, such as to make the best use of the great effort expended in collecting and accumulating a given stock of specialized terminology. The inevitable compromise between available space and entries in four languages seems to have been struck fairly happily here. Although much is missing that one would wish to see included, the available material is up to date, skilfully arranged and cross-indexed and is probably sufficient to meet the needs of most industrial readers of the various German, French and Italian nuclear journals. It has obviously been compiled on the basis of extensive expert consultation, and none of the classical terminological pitfalls with which the user of less carefully compiled dictionaries is often faced has been found by the reviewer.

One would wish this dictionary sufficiently brisk sales to encourage its compiler to undertake early a new, expanded edition on the same lines.

L.C.R.

World News



These recent pictures show the current progress at Bradwell nuclear power station in Essex. (Above) The building for number two reactor is in an advanced stage. The station is expected to start operating next year.

(Left) The vault of number two reactor at Bradwell. The top view shows the thermal dome.

International

EURATOM have reported increasing atmospheric radioactivity over Europe and scientists will meet this month to study the rise. The average level of radioactivity has remained below that of the basic standard set by the Commiss.on, however.

SPECIAL TRAINING FACILITIES and fellowships, totalling nearly 200, have been made available to the IAEA by 12 countries. In addition a considerable number of fellowships will be financed from the agency's own operating fund.

THE U.S.-EURATOM Joint Research and Development Board will meet early this month to consider proposals under the U.S.-Euratom agreement.

United Kingdom

A RESEARCH ESTABLISHMENT, costing about £1 million, is to be built by the CEGB next to the Berkeley nuclear power station in Gloucestershire. The centre will consist of engineering, physics, metallurgy and chemistry laboratories and will employ between 150 and 200 people. When choosing the site for the centre, the CEGB state they took into consideration the proximity of Berkeley to several important universities.

BECAUSE of a long series of unofficial strikes, Motherwell Bridge and Engineering have threatened to stop working at Hunterston. The company are reported to be six months behind in providing the steam-raising equipment. Latest news is that a new agreement between the company and the Boilermakers' Society, whose members have been responsible for three-quarters of the strikes, is expected to be reached shortly.

ROLLS-ROYCE and Westinghouse Electric of the U.S. have signed a contract for the supply of the reactor to power Britain's first nuclear-powered submarine, *Dreadnought*. The reactor and machinery will be similar to that being installed in the latest American nuclear submarines of the *Skipjack* class. The agreement also covers the fissile fuel needed for the reactor and provides for the Navy being able to obtain fuel up to 1968. First Lord of the Admiralty, the Earl of Selkirk, is reported as saying that the decision to equip the submarine with an American reactor will result in it being completed one year sooner than would otherwise have been possible.

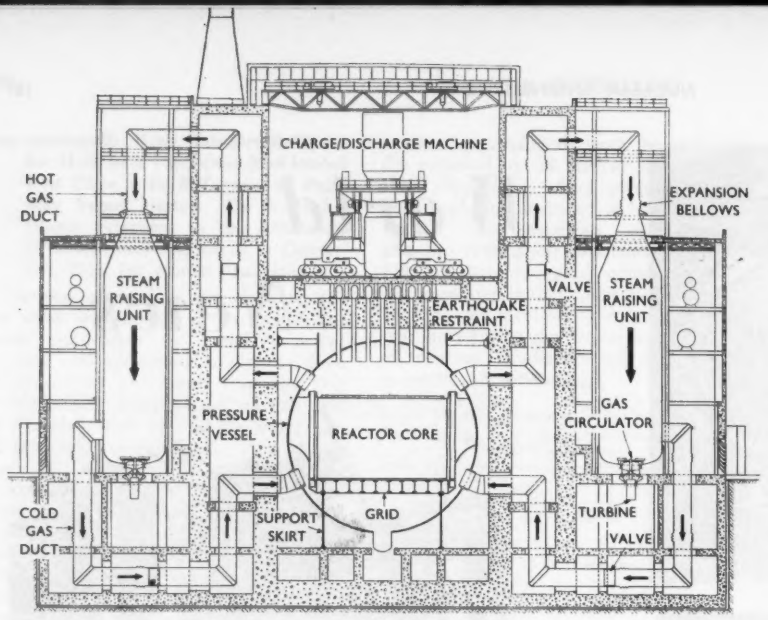
CONTRACT for the design of a plant for recovery of radioactive caesium from highly active waste materials has been placed with W. J. Fraser and Co. by U.K. AEA.

THE CONSTRUCTION of the pipeline to take effluent from Winfrith Heath into the sea has begun. The pipeline will stretch five miles overland from Winfrith and for about a further two miles out to sea. John Brown will build the first four miles and Taylor Woodrow, in association with Collins Submarine Pipelines, the remainder.

NEGOTIATIONS between G.E.C. Simon-Carves and Japan for the building of a nuclear power station at Tokai Mura, 65 miles from Tokyo, are still under way. Expected to cost £30 million the design of the plant incorporates many earthquake-proof devices. G.E.C. Simon-Carves learnt last month that they had been chosen to enter into negotiation for the plant.

THE PROPOSAL by the CEGB to build a nuclear power plant at Sizewell has been accepted by the East Suffolk County Council. No public inquiry will be held. CEGB have also announced that preliminary investigations are to be made as to the suitability of sites on the north coast of Anglesey for nuclear power plants.

U.K. AEA have announced a reorganization of their isotope production and marketing division to meet the increase in demand for radioactive isotopes.



A simple cross-section of the proposed power plant by G.E.C. Simon-Carves to be built at Tokai Mura, Japan. The 150 MW plant has had a number of features incorporated to withstand earthquakes. Because of the site conditions at Tokai Mura, G.E.C. are not using the bottom charge and discharge machinery which was adopted for Hunterston.

Australia

RADIOACTIVE PITCHBLENDE discovered at Radium Hill is ten times richer than any uranium ore so far mined in this area. This is the first pitchblende discovered at Radium Hill, most of the ore mined contains Davidite.

THE ANNUAL REPORT of the Atomic Energy Commission gives a warning regarding the supply of uranium unless reserves are expanded. The report states that uranium production at Rum Jungle declined last year owing to lower grade raw material.

British Guiana

THE GOVERNMENT has now asked Mitchell Engineering to work out a detailed scheme for the introduction of nuclear power. The plant is expected to cost about $15 million.

Canada

A 10 MeV tandem accelerator is now in operation at Chalk River at the laboratories of Atomic Energy of Canada. The accelerator was designed and built by High Voltage Engineering of Burlington, Mass.

GROUP PROFITS of Rio Tinto Mining rose in 1958 to $488.5 million compared with $121.8 million previously and value of uranium produced and delivered totalled $120.4 million as compared with $57.1 million in 1957.

Denmark

THE DANISH Atomic Energy Commission and the O.E.E.C. European Nuclear Energy Agency, will hold a symposium for health physicists from nuclear energy centres or installations at Risø, May 25-28. Scientific aspects, including radiation protection, control of radioactive contamination and emergency measures, will be discussed.

THE FINSESN INSTITUTE will conduct a three-year examination of radioactive effects on human beings under normal conditions.

Germany

WEST BERLIN UNIVERSITY opened a new nuclear institute on March 14. The university's 50-100 kW research reactor went critical on the same day.

THE BADEN-WURTTEMBERG study group have rejected three British tenders for a 100 MW nuclear power plant and are now considering three American tenders. The decision has apparently been made on purely economical reasons. The American tenders being considered are by Westinghouse, Babcock and Wilcox and Atomics International.

Italy

AN APPEAL has been issued by the National Committee for Nuclear Research to the Prime Minister, Signor Segni, for the Government to submit to Parliament a Bill regulating nuclear research and the exploitation of nuclear energy. In its appeal the committee has stated that early authorization of an expenditure of £60 million over five years was vital. The Government has indicated that positive steps might be taken this session.

Iraq

IN DEPOSITING an instrument of ratification of the Statute of the IAEA, Iraq has become the seventieth member of the Agency. IAEA came into being on July 29, 1957.

Japan

A ZERO ENERGY pilot reactor of the semi-homogeneous, high-temperature, gas-cooled breeder type, is to be built by the Atomic Energy Research Institute. The design specification has been completed and the invitation to submit the tender estimate has been issued to six private nuclear groups in Japan. The reactor is expected to be completed by September, 1959.

THE URANIUM REFINING PLANT at Tokai Mura has been completed by the Atomic Fuel Corporation. The test run of the plant was successfully started on December 18, 1958, and is now in full operation. Capacity of the plant is one ton of metallic uranium per month and the ingots produced will be 5 in. in diameter weighing 100 kilograms. The first throughput was recently completed, using 8 tons of yellow cake imported from South Africa.

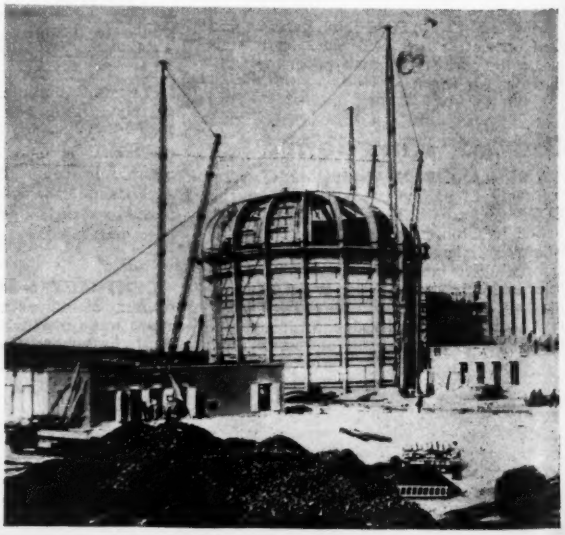
Netherlands

NERATOOM, a limited company to serve the Dutch industry in the construction of land-based nuclear installations is to be formed by six important companies, Phillips, Machinefabriek Breda, Rotterdamsche Droogdok, De Schelde, Stork and Werkspoor.

South Africa

URANIUM at 68s. per lb for small quantities is being offered on the free market by the Atomic Energy Board. The price covers supplies of up to 25 tons of calcinated concentrate at 86%, which would be suitable for research purposes.

BURSARIES are to be awarded by the Atomic Energy Board to successful candidates for study in nuclear energy, providing they work for the Board on the completion of their studies.



A general view of the Dutch nuclear centre at Petten showing the housing for a high flux reactor. The centre is for research and development only and will include a radio-chemical laboratory.

Sweden

IN THEIR INVESTIGATION of heavy-water, gas-cooled reactors, Aktiebolaget Atomenergi have asked Hawker Siddeley Nuclear Power, of the U.K., to examine heat-transfer characteristics of fuel element bundles. Experimental elements with longitudinal and spiral fins are being tested singly in a 4-ft long channel and will later be tested in groups of 19, having a maximum rating of 190 kW per ft of channel. The surface heat rating of the alumina insulated electrical heaters being used, is 135 W/cm².

Yugoslavia

IAEA ARE TO SEND two scientists to the Boris Kidric Institute at Vinca where the radiation accident, involving six scientists took place, to study the pattern of circumstances that led to the accident.

Venezuela

A 3MW REACTOR will be finished by the end of this year. Total cost, including laboratories and buildings is about $5.4 million. This will be Venezuela's first reactor.

U.S.S.R.

EQUIPMENT for a mobile 2 MW water-water nuclear power plant will soon be completed. Housed in a frame with a diameter of about 3½ ft and nearly 7½ ft high, the reactor will use ordinary water under a pressure of 120 atmospheres as a coolant and moderator. The secondary circuit will be a turbine operating on steam at a pressure of 20 atmospheres and at 280°C.

U.S.A.

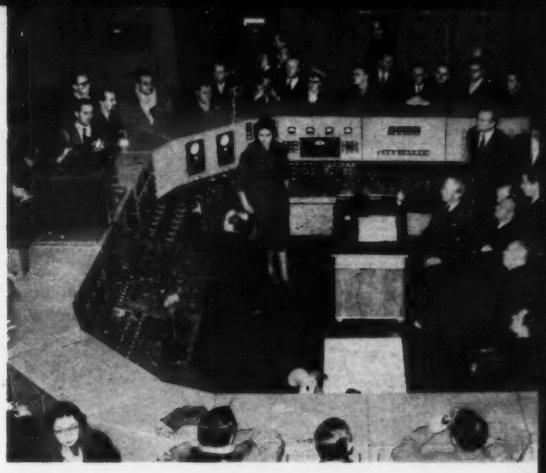
A DELAY of nearly a year in the construction of the nuclear powerplant at Indian Point is announced by Consolidated Edison. The company have told the Joint Congressional Committee that unexpected technical problems have arisen and that the plant is now expected to cost $100 million, nearly double the original estimate.

A NEW INDUSTRIAL GROUP, comprising the Isbrandtsen Company, Maryland Shipbuilding and Drydock and Ford Instrument, division of Sperry Rand, for more rapid progress towards nuclear merchant ships, has been formed.

A TOTAL OF 440 AWARDS of unclassified research and development contracts in physical sciences to various colleges, universities, private research institutions and industrial concerns, was made by the AEC during 1958.

A PUBLIC HEARING to investigate the financial qualifications of the Yankee Atomic Electric to design and construct a nuclear power station will be held in the AEC, Germantown, Maryland, headquarters. The company are building a 110 MW pressurized water nuclear power plant at Rowe, Mass.

ONE CONSTRUCTION PERMIT and four licences, authorizing operation of research reactors during the period January 15 to February 13, were amended by the AEC. During January the Commission also granted or amended 32 special nuclear material licences and issued 19 operators' licences for reactors.



On his recent visit to the U.S.S.R. the Prime Minister, Mr. H. Macmillan was shown the nuclear research centre at Dubna. Here he is seen in the control room of the institute.

A SMALL-SCALE field study of the possibilities of disposing radioactive wastes in natural salt formation will be undertaken by Carey Salt of Hutchinson, Kansas, under an agreement signed with the AEC.

DISPOSAL of radioactive waste material in the Pacific Ocean will be undertaken by Coastwise Marine Disposal of Los Angeles under AEC licence. The waste packages will have sufficient density to ensure sinking to a depth of 6,000 ft.

LOS ALAMOS Scientific Laboratory have completed an investigation of the radiation accident at the laboratory which killed an employee on December 30, 1958. The committee reporting on the findings declare that the accident was directly attributable to errors on the part of the deceased operator during a series of transfers of plutonium and organic solutions between containers in a chemical plutonium recovery process.

NORTH CAROLINA State College have been given notice by the AEC that it will receive a construction permit for the relocation of a low-power training reactor on its campus at Raleigh.

A CONTRACT has been signed by the AEC with East Central Nuclear Group for research and development on a gas-cooled nuclear power plant in the Florida West Coast area. Research to develop heavy-water moderated, gas-cooled, pressure-tube reactor will cost about $18 million.

IN RESPONSE to industrial requests for krypton-85, the AEC has increased the availability of this radioisotope for civilian use to 100,000 curies per year.

THE DISCOVERY of an atomic particle, the Xi-Zero or neutral cascade hyperon, has been announced by a group of scientists at the University of California's Lawrence Radiation Laboratory. The particle, with a mass of about 40% greater than that of a proton, has a zero electrical charge and exists for only a few billionths of a second. When it decays it disintegrates into two zero-charged products.

A NEW LABORATORY for studies on plutonium is being constructed at the nuclear research centre near Columbus, Ohio.

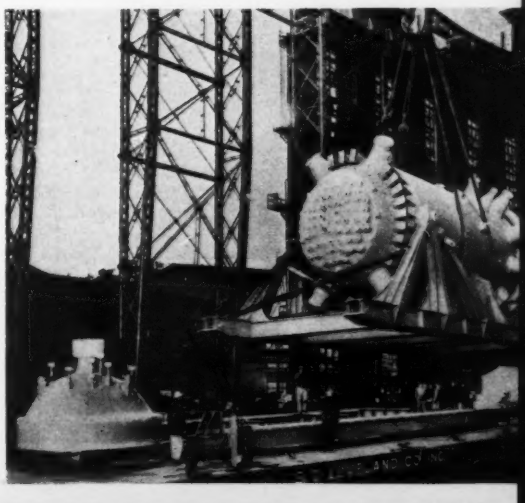
UNIVERSITY OF WYOMING in Laramie has received permission from the AEC to construct an L-77 low-power, solution-type, light-water moderated reactor. It is designed to operate at a thermal power level of 10 kilowatts using enriched uranyl sulphate.

AMOUNT OF RADIOISOTOPES shipped from Oak Ridge National Laboratory for use in peaceful applications of nuclear energy increased by 37% during 1958.

MAJOR ADDITIONAL construction to Oak Ridge National Laboratory, totalling $6,130,000, will be undertaken by J. A. Jones Construction of Nashville, Tennessee. The additions will virtually double the size of the existing buildings.

A MODULAR NUCLEAR powerplant proposal by The Martin Company has been selected by the AEC as a basis for contract negotiations from among nine received. The plant is to be installed and operated at the Sundance Air Force Station, Wyoming.

A HELIUM LIQUEFIER, recently installed, has enabled scientists at the Oak Ridge Laboratory's Solid State Division to reduce the temperatures of samples placed in the centre of the graphite research reactor to approximately 3.6°K.



This is the Commonwealth Edison Dresden nuclear power station's reactor vessel on its way to the site. The vessel weighs 300 tons, is 42 ft high and 20 ft wide. Interior diameter is 12 ft and the walls are 5½ in. thick.

Personal

Lord Plowden.

Dr. N. Levin.

Mr. J. C. Duckworth.

Earl of Halsbury.

Appointments

Lord Plowden will become managing director of British Aluminium and vice-chairman of Tube Investments next year. His term of office at the AEA expires at the end of this year.

Sir William Penney as executive head of the AEA Research Group. **Sir William Cook** as executive head of the AEA Development and Engineering Group. **Sir Leonard Owen** as executive head of the AEA Production Group.

Dr. F. A. Vick, head of the physics department, University College, North Staffordshire, as deputy director of AERE, Harwell.

Sir John Cockcroft as a member of the Court of the University of London.

Mr. H. H. Mullens as chairman of Anglo Great Lakes Corporation. **Mr. H. B. Topham** becomes general manager and **Mr. D. P. Walton** a director.

Dr. N. Levin as director of AEA Weapons Group to succeed Sir William Penney. **Mr. E. F. Newley** becomes deputy director.

Mr. J. C. Duckworth as managing director of the National Research Development Corporation.

Lord Halsbury as vice-chairman of the Lancashire Dynamo Group.

Mr. H. G. Nelson as industrial leader and vice-chairman of the Advisory Council on Middle East trade.

Mr. L. Malec as managing director of Solartron Radar Simulators.

Mr. I. M. Stewart and **Mr. J. H. Lord** to the board of G. and J. Weir Holdings.

Mr. F. J. Fagard as managing director of Power Jacks.

Sir Alexander Fleck as president of the Industrial Co-partnership Association.

Mr. F. H. Hoult as managing director, **Mr. J. H. Grainger** an executive director and general manager, and **Mr. J. E. Wigley** an executive director and secretary of Constructional Engineering.

Mr. F. J. Fagard.

Mr. L. Malec.

Mr. T. Sanderson and **Mr. J. Laird** to the board of Workington Iron and Steel.

Mr. M. H. Taylor to the board of British Engineers Small Tools and Equipment.

Mr. R. F. Hunt as deputy chairman of the Dowty Group.

Mr. N. D. Naiden as a deputy general counsel of the U.S. AEC.

Mr. M. F. Ippolito as president, **Mr. M. M. Beckenabuer** and **Mr. H. C. J. H. Gelissen** as vice-presidents of the Consultative Committee of Euratom.

Mr. T. LeClair as chairman of Internuclear, Missouri.

Mr. H. V. Slade as chairman of the Radio and Electronic Component Manufacturers' Federation.

Mr. H. F. Wilson and **Mr. C. L. G. Fairfield** as directors of Submarine Cables.

Mr. R. D. Baird a director of Baird and Tatlock (London). **Mr. R. T. Beasley** becomes personnel manager of the company.

Mr. D. W. Hawkins to the board of Dunlop Rubber.

Dr. D. J. Peery and **Dr. J. C. Stewart** as research members, General Dynamics, Atomic Division.

Institute of Metals, Council announce the following: **Mr. G. L. Bailey,** president; **Lord Tedder,** past-president; **Mr. H. Ford, Mr. E. H. Jones** and **Mr. H. O'Neill,** vice-presidents; **Mr. D. P. C. Neave,** honorary treasurer; **Mr. W. O. Alexander, Mr. N. P. Allen, Mr. F. Dickinson,** and **Mr. L. Rotherham,** ordinary members of the Council.

Mr. J. G. Marsden as general sales manager of Anti-Dust Services.

Mr. N. G. Bennett as joint managing director of Graviner.

Major-General Sir Francis de Guingand and **Mr. E. L. Burton** to the board of Tube Investments.

Mr. N. C. Macdiarmid as chairman of the Council of Iron Products.

Mr. L. T. Hinton as chairman, **Mr. R. R. C. Rankin** as vice-chairman of the Electronic Engineering Association.

Mr. W. A. May as director of Berry's Electric.

Mr. A. T. Mayne as general manager for the Middle East of Taylor Woodrow.

Mr. J. F. Willsher as general works manager of George Kent.

Central Electricity Generating Board announce the following: **Mr. E. M. Packham** as secretary and **Mr. H. Marriott** as accountant of Eastern, London and South Eastern region; **Mr. E. V. Hardaker** as divisional electrical engineer, Midlands and East Midlands region.

Mr. A. Cormack, superintendent, Larne Works, and **Mr. R. Harrison,** assistant superintendent, Germiston Works, of Metropolitan-Vickers.

Mr. R. A. le Page as managing director of Macuna Engineering.

Mr. F. C. Boys as commercial assistant to the production manager of Electro-Acoustics department of Phillips Electrical.

Mr. W. H. McFadzean as president-elect of the Federation of British Industries.

Mr. J. R. Hughes to the board and as commercial manager of Hivac.

Mr. J. C. Ward as chairman of Heavy Minerals.

Mr. S. Oestreicher as export sales manager for nuclear products of American Machine and Foundry.

Awards

Prof. J. Diamond, Professor of Mechanical Engineering at Manchester University, the Constantine Medal for 1959 by the Manchester Association of Engineers for his paper on welding techniques.

Dr. L. B. Pfeil the Institute of Metals (Platinum) Medal.

Professor R. W. K. Honeycombe the Rosenhain Medal.

Dr. R. B. Sims, the W. H. A. Robertson Medal and Premium.

Tours

Dr. J. M. Fletcher, AERE, Harwell, for a British Council lecture tour of Finland and Sweden.

Mr. H. G. Campbell, managing director, and **Mr. J. O. K. Purdey,** sales director of Benjamin Electric to India, Malaya, Australia, New Zealand and the United States.

Sir Leonard Owen, managing director of AEA's Industrial Group to Australia, New Zealand and Canada, to give general lectures on nuclear energy.

Retirement

Dr. W. F. Libby, Commissioner of the U.S. AEC, will leave his post on June 30 to concentate on research and teaching.

Obituary

Nuclear Engineering regret to announce the deaths of the following:—

Mr. W. J. Picken of English Electric Valve at the age of 72.

Capt. G. R. Cook, London manager of Cockburns.

Governor P. Ryckmans, Belgian Atomic Energy Commissioner, on February 18.

Industrial Notes

Imperial Smelting Corporation have announced plans for commercial production of nuclear grade beryllium metal. New plant being installed at their Avonmouth plant will be completed by the end of the year when production is expected to commence. This will be the first commercial production of virgin beryllium metal in the U.K.

U.K. AEA, Industrial Group have placed a contract with **John Brown and Co.** for the refuelling machine for the advanced gas-cooled reactor at Windscale.

David Brown Industries have signed an agreement for the exclusive manufacturing rights in Britain of a patent form of radiation shielding perfected by Knapp Mills of New York. Manufacture of the shielding will be undertaken by the David Brown Jackson Division at Salford, Lancashire.

International Computers and Tabulators have received an order from the C.E.G.B. for the rental of an I.C.T. Type 555 electronic calculator for stores and cost accounting, mathematical applications and nuclear fuel element calculations.

The Fifth International Instrument Show sponsored by B. and K. Laboratories will be held at 4 Tilney Street, Park Lane, London, April 6-10.

Central Electricity Generating Board are to erect a 275 kV overhead double circuit supergrid line from a point near Boxted, south west of Lower Halstow, to a proposed situation at Canterbury. The Board has placed contracts totalling £14.1 million during the past two months.

Dunlops have developed an extra high pressure flexible hose for conveying gases and fluids. The hose, reinforced by three high tensile steel braids, is of 1¼ in. diameter bore and has a working pressure of 4,000 p.s.i. Operating temperatures for fluids or gases are up to 130°C and ambient temperatures are from minus 30°C to plus 100°C.

Southern Areas Electric Corporation have announced the merger of two of their subsidiary companies. **Tyer and Co.** will take over the precision engineering and electronic equipment firm of **P.A.M. Ltd.**

W. H. Allen Sons have received a contract from the AEA for two diesel engine driven generator sets for the advanced gas-cooled reactor at Windscale. The two engines are 12-cylinder, vee-form, pressure-charged, Allen type VBS 12 running at 600 r.p.m. and driving a 600 kW, 240 V Allen d.c. generator.

CVA Small Tools have moved their London office to 48 High Street, Edgware, Middlesex. Tel.: Edgware 4488.

Sixth Post Graduate Nuclear Engineering Course at Manchester University will be from May 5-July 3. Applications should be sent to Mr. A. Davies, Registrar's Dept. The course consists of lectures, discussions and practical classes directed towards reactor technology.

Lancashire Dynamo Electronic Products have announced substantial price reductions for their T.L.C. transistorized level control equipment.

Ashmore, Benson, Pease have recently concluded a licence arrangement with **Mond Nickel** enabling them to supply S.G. or high ductile iron castings in accordance with British Standard Specification 2789/1956.

Wild-Barfield Electric Furnaces have announced a price reduction in their Carbodrip gas carburizing fluid.

Combustion Engineering, New York, have acquired the **General Nuclear Engineering Corporation.** The company will now operate as a subsidiary of Combustion Engineering.

High Voltage Engineering, Burlington, Mass., manufacturers of radiation-producing particle accelerators, are to establish a manufacturing plant in Amersfoort, Netherlands.

The British Trade Fair at Lisbon will be held from May 29 to June 14.

The annual report of the **Radio and Electronic Component Manufacturers' Federation** states that production of the industry increased in 1958 by 9% to £287 million.

The Corrosion Exhibition will be held in the Royal Horticultural Society's New Hall, London, S.W.1, April 27-30.

The British Standards Institution has revised B.S. 1407 for high carbon bright steel and issued B.S. 3082 for mechanical testing of steel at elevated temperatures.

Mullard's are holding a special electronics exhibition at the Electronics Centre, Mullard House, April 6-10.

Permali have reduced the price of their Permaflon P.T.F.E. by an average of 10%.

A new high voltage laboratory for **British Insulated Callenders Cables** is now in commission at Erith.

Meetings

April 1.—Institution of Electrical Engineers (Cleveland Scientific and Technical Institute, Corporation Road, Middlesbrough, 6.30 p.m.) "Electrification of the U.K.A.E.A. Industrial Group Factories," J. W. Binns and W. J. Outram.

April 3—Society of Chemical Industry (Chemical Eng. Group) (Robinson Lecture Theatre, Manchester University, Oxford Road, Manchester, 13). "Titanium and its Alloys as Materials of Construction for Chemical Plant," Dr. K. W. J. Bowen.

April 6.—The British Institution of Radio Engineers (London School of Hygiene and Tropical Medicine, Kebbel Street, Gower Street, W.C.1, at 3 and 6 p.m.). Symposium on "Large Capacity Storage Devices."

April 8.—Institution of Electrical Engineers (North-Western Electricity Board Lecture Theatre, Jubilee Street, Blackburn). "Thermonuclear Processes with special reference to Zeta," E. R. Hartill.

April 10.—Institution of Electrical Engineers (South Dorset Technical College, Weymouth, at 6.30 p.m.). "Thermonuclear Reactors," D. W. Fry.

April 10.—Institution of Mechanical Engineers (1 Birdcage Walk, Westminster, London, S.W.1, at 6 p.m.). James Clayton Lecture. "Canadian Atomic Energy Development in Review and Prospect."

April 15.—Institution of Electrical Engineers (North-Western Electricity Board Demonstration Theatre, Duke Street, Barrow-in-Furness). "Electrical Installation at Calder Hall Nuclear Power Station," N. J. Mackay and E. Hardwick.

April 15—Institution of Chemical Engineers (joint meeting of North Western Branch with Institute of Petroleum, The Blossoms Hotel, Chester). "High vacuum technology in the chemical industry," A. S. D. Barrett and T. W. G. Rowe.

April 16—I.O. Welding—S.L. Branch (54 Princes Gate, S.W.7). "Welding in Nuclear Engineering," H. E. Dixon.

April 17.—Institute of Physics (47 Belgrave Sq., London, S.W.1). "Current Developments in the Production of High Vacua."

April 22.—The British Institution of Radio Engineers (London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1, at 6.30 p.m.). "The Application of Magnetic Resonance to Solid State Electronics," by D. J. E. Ingram.

April 28—Health Congress at Harrogate (Chadwick Trust, 5.30 p.m.). "New Factors in Man's Management of His Environment especially radiation, fluoridation and air pollution," Dr. Gordon Fair.

April 29—Health Congress at Harrogate, Section K (5 p.m.). "Radiation Levels and their Significance," W. V. Mayneord. "Radiation Protection in the Design and Operation of Nuclear Power Stations," J. C. Duckworth.

April 29.—Powder Metallurgy Joint Group (Church House, Great Smith Street, Westminster, S.W.1, 9.30 a.m.). "Theoretical Aspects of Sintering."

April 29-30.—Institution of Electrical Engineers (Savoy Place, London, W.C.2) (in conjunction with the British Nuclear Energy Conference). Convention on Thermonuclear Processes.

Catalogues

Argonne National Laboratories describe reactor fuel processing in the January issue of *Technical Progress Reviews*. (U.S. Government Printing Office, Washington 25, D.C.)

A section of nuclear propulsion for ships is included in the **Lloyd's Register of Shipping,** annual report for 1958. (71 Fenchurch Street, London, E.C.3.)

British Electrical and Allied Manufacturers' Association have produced a booklet of abbreviations of associations, institutions and research and trade associations. (36 Kingsway, London, W.C.2.)

The **European Productivity Agency** booklet, No. 31, contains an article on nuclear science with regard to agriculture research. (3 Rue Andre-Pascal, Paris, 16.)

A new catalogue of radioactivity measuring instruments has been produced by **Nuclear-Chicago.** (229 West Erie Street, Chicago 10, Illinois.)

Uranium-Aluminium Fuel Elements is the title of a new technical data bulletin produced by **M. and C. Nuclear.** (P.O. Box 898, Attleboro, Mass.)

The latest edition of the quarterly review, *Atomic Energy*, published by the **Australian Atomic Energy Commission** contains an article on the prospects of nuclear power for South Australia. (P.O. Box 5343, Sydney.)

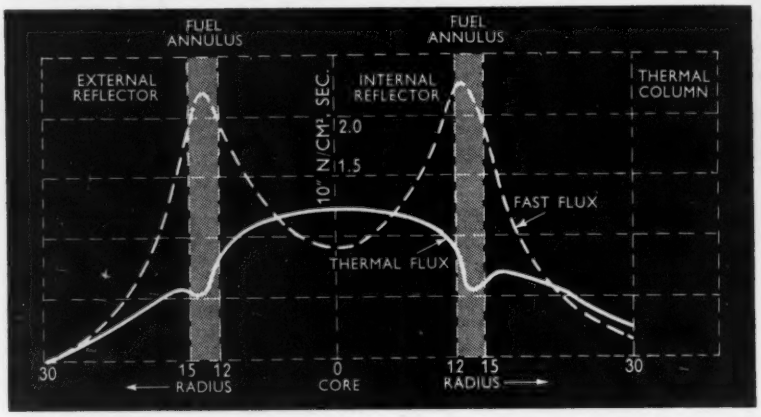
Processes and Equipment

For further information on any item please enter the relevant number on the Reader Service Card enclosed with this issue and forward the card to the address given.

Hawker Siddeley Build Research Reactor

Details are now available of the research reactor which Hawker Siddeley Nuclear Power Company are building at Langley. The 10 kW JASON system, is based on the ARGONAUT design of the Argonne National Laboratories, which was demonstrated at Geneva last September. JASON can be used for many nuclear physics experiments, the production of isotopes, neutron therapy and radio chemistry. The first reactor will provide designers at Hawker Siddeley with useful additional facilities for the study of nuclear plants for ships, electricity production and heat production.

Operating at 10 kW using enriched uranium fuel elements, similar to those in the DIDO and PLUTO reactors at Harwell, JASON provides a large source of neutrons at low power giving rapid measurements on neutron absorption of materials including fuels. The water-moderated reactor is of the thermal heterogeneous type, having an annular core with internal and external reflectors. Maximum flux is about 1.5×10^{13} neutrons/cm², sec at a power level of 10 kW. The central region is basically a cube of graphite containing a centrally located water annulus formed by two aluminium tanks, one 2 ft in diameter and the other 3 ft. An internal graphite reflector of 2 ft diameter has a central hole and four additional holes which may be used for pile oscillator measurements and danger coefficient experiments. The control rods are in the external graphite reflector leaving the top face free of control mechanisms. This helps the loading of fuel assemblies, the placing of experiments in the internal reflector and the positioning of external exponential experiments directly on top of the core. The internal reflector is removable so that the central position can be used for internal exponential experiments. A thermal column containing 14 horizontal experimental ports is adjacent to one face of the graphite reflector. Against the opposite face there is a mobile flat-bed truck on which is mounted a water tank in which shielding experiments may be performed. Two further experimental ports are horizontally placed in the two other opposing faces giving a total of 21 horizontal and vertical access ports. The fuel elements, located between two aluminium tanks, consist of a uranium oxide/aluminium mixture clad in aluminium and are assembled in boxes to give about 350 g of U^{235} per box. The boxes are interspaced with graphite fillers so that the annulus is completely filled.



Flux distribution curves for the JASON research and training reactor under construction by Hawker Siddeley Nuclear Power. The radius dimensions are in inches.

Purified light water acting as a moderator and coolant passes up between the fuel plates in the annulus. The water circulates in a closed loop losing its heat in a heat exchanger.

JASON provides a controlled source of neutron and gamma radiation for studying radiation effects on materials and biological specimens and for the testing and calibration of radiation instruments. It can also be utilized as an analytical tool for industrial process control and can be used in association with conventional laboratory equipment to obtain control information to a degree of accuracy that is not possible with standard methods. An additional use of the reactor is as an extremely sensitive analytical probe capable of detecting the presence of trace elements by standard activation techniques.

Hawker Siddeley expect to complete the first JASON next September.

(Hawker Siddeley Nuclear Power Company, Ltd., Sutton Lane, Langley, Bucks.)

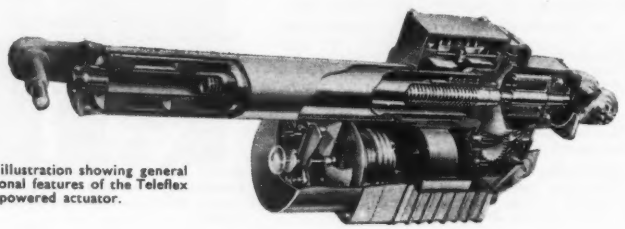
1187

Counter with Electrical Reset

Counting Instruments are now able to supply their Type 100 electric counter with electrically operated resetting facilities. This is in the form of a solenoid mounted at the rear of the case, which, momentarily energized, operates the resetting mechanism to return the counter reading to zero. The counter incorporates an improved balanced escapement mechanism. One of the advantages of this form of resetting is that a number of counters can be reset to zero at the same time by operating a switch which can be situated remotely from the counters. The counter can be electrically reset when operating without causing any damage to the counter mechanism.

(Counting Instruments, 5 Elstree Way, Boreham Wood, Herts.)

1188



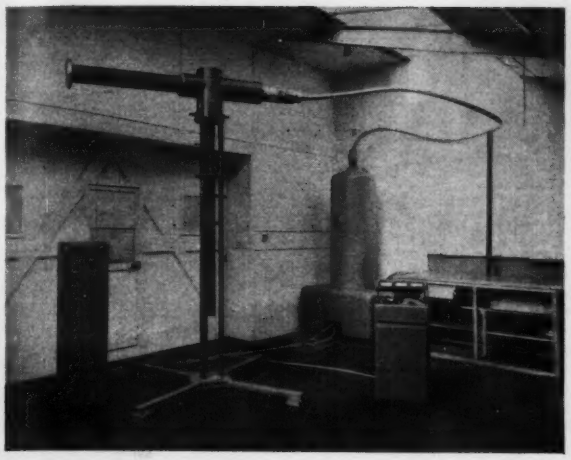
Cut-away illustration showing general constructional features of the Teleflex powered actuator.

Powered Actuator

An electrically powered actuator for controlling mechanical movement, has been developed by Teleflex Products. The actuator is basically an electro-mechanical screw jack capable of performing similar functions to hydraulic and pneumatic jacks. The jack can be stopped at any desired position instantly. It will hold the load indefinitely at any setting and does not require a separate motive unit, merely being connected to the electricity supply. The operating motor is normally wound for a 3-phase, 50-cycle, 400-volt supply but motors for other voltages can be supplied. A low-voltage system, 48 volts, is used for signalling to the control room and for indicating lamps, and a 12-volt supply is employed for the indicating system. Power output can be set to any predetermined value and may be varied from 40 to 4,000 lb Standard stroke is 12 in. and ram speed 32 in. per minute. The actuator can be operated manually in the event of a mains failure.

(Teleflex Products, Ltd., Basildon, Essex.)

1189



(Above) The 600 kV generator marketed by Miles Hivolt.

New 600 kV Generator

Built by SAMES of France and marketed in the U.K. by Miles Hivolt, the SAMES 600 kV generator is capable of delivering up to 600 kV at 4 mA. Because of its relatively small size and low weight (just over 2,000 lb), the generator is ideally suited for testing cables and switchgear. It can be assembled in a mobile unit to carry out field tests on high voltage transmission lines.

The generator can also be used as a high voltage accelerator for both ions and electrons. When used for the former, it provides a neutron source which can be switched on and off at will.

(Miles Hivolt Ltd., 91 Princedale Road, London, W.1.)

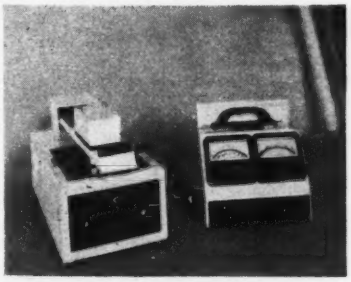
1190

Personnel Protection Densitometer

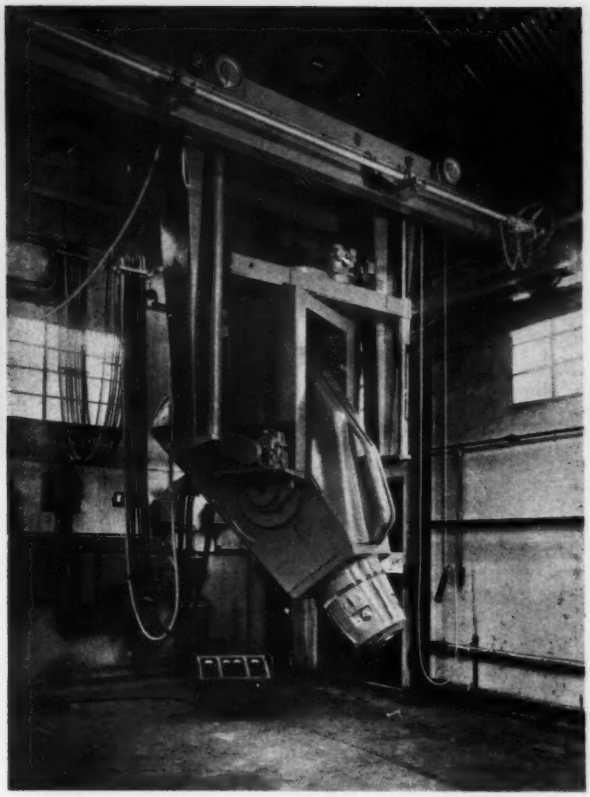
A new equipment designed for rapid and accurate measurements of density of processed personnel protection film badges is being marketed by Baldwin Instruments. The instrument enables low levels of density to be measured with a high degree of accuracy. It can also be used as a precision general purposes densitometer. The densitometer comprises two units, a controlled light source and a vacuum photoelectric cell with a d.c. amplifier. The unit light is fed from a constant voltage transformer whilst a coarse and fine rheostat controls the level of illumination. The measuring table is of sufficient area to enable large X-ray plates to be handled. The standard instrument has two viewing apertures, one of $\frac{3}{16}$-in. and the other of $\frac{1}{16}$-in. diameter.

(Baldwin Instrument Co. Ltd., Brooklands Works, Dartford, Kent.)

1191



Baldwin equipment for measuring the density of processed film badges.



Mullards' 5 MeV linear accelerator designed specifically for industrial radiography.

Linear Accelerator

The 5 MeV linear accelerator shown in an accompanying illustration is installed at a Ministry of Supply Establishment. It is believed to be the first of its kind designed specifically for industrial radiography. The output is more than 500 röntgens/minute at 1 m distance and the electron beam creating the X-rays has a diameter of less than 2 mm when it strikes the target. It has a penetrating power of 8 in. to 10 in. and is to be compared with multi-curie radioisotope cobalt-60 sources which give only 5-in. penetration. Reference to this type of testing equipment for use in connection with reactor pressure vessel construction has been made by Sir Leonard Owen in his lecture reported on page 179.

(Mullard Ltd., Torrington Place, London, W.C.1.)

1192

Glass-lined Vessels

Details of a new range of acid-resistant glass-lined steel equipment for use in the chemical and pharmaceutical industries have been announced by QVF, the industrial engineers in glass.

The pressure and vacuum resistant equipment gives a high degree of resistance to chemical attack; to extreme temperatures, and to sudden changes in temperature caused by heating and cooling processes. The non-porous glass enamel coating used in the tanks and vessels consists of several layers and may be exposed to temperatures of up to 250°C and to reductions as low as −50°C, without risk of damage.

The elasticity and working qualities of the glass enamel have been developed to a degree where the advantages are resistance to abrasion, thanks to the hardness of the glass enamel, and reduction of ingredient adhesion which facilitates hygienic cleansing. The equipment includes open vessels, evaporating pans, open and closed jacketed tanks, receivers, an extensive range of reaction kettles; storage tanks, heat exchangers and stuffing boxes. Capacities vary in most cases from 40-8,000 litres.

(QVF Ltd., Fenton, Stoke-on-Trent.)

1193

γ-ray Proportional Counter

The type PX.115 proportional counter by 20th Century Electronics is a high resolution proportional counter originally developed for the γ-ray spectrometer. The energy resolution of a proportional counter below 100 keV is better than that of a scintillation counter and its employment extends the range of scintillation γ-ray spectrometers to 20 keV. γ-ray spectrometers are widely employed in the analysis of spectra such as that from fission products and the high resolution of the energy resolution have been made using an americium-241 source which emits γ-rays of 59.4 keV. The best resolution which has so far been obtained with these counters is 5.6%. Over the operating range, the gas multiplication factor is 60 volts/db.

(20th Century Electronics Ltd., King Henry's Drive, New Addington, Croydon, Surrey.)

1194

Patents Reviewed

These abstracts have been made from British Patent Specifications, complete copies of which can be obtained from the Patent Office, 25 Southampton Street, London, W.C.2, at 3s. 6d. each (including postage).

B.P. 800,420. Process for the manufacture of fuel elements for nuclear reactors. Deutsche Gold- und Silber-Scheideanstalt vorm. Roessler (Germany).

In order to facilitate heat transfer between the fuel (uranium) and the body of the can, it is proposed to fill the free space inside the loaded can with pure magnesium or an alloy of high magnesium content. A (steel) can, suitable for the purpose, is described. The tube, substantially longer than the fuel rod, is permanently closed at one end and has an opening of about 0.5 mm dia. at the other. In applying the method, the can is evacuated after loading and subsequently the magnesium, in the molten state, is fed into the can through the opening under the action of compressed inert gas. Finally, the opening is sealed off, either by welding or by means of a plug.

B.P. 800,426. Separating and purifying zirconium and hafnium. Commissariat à l'Energie Atomique (France).

An aqueous and (nitric) acid solid solution (preferably of a concentration of 0.2% N) is formed from the ore containing zirconium and hafnium. This solution is treated with a solvent, such as alkyl phosphate or acetate, or an alkyl-aryl phosphate or acetate, which permits extraction of the zirconium without affecting the hafnium in the solution.

B.P. 800,526. Process and apparatus for effecting nuclear fission reactions. Stichting Reactor Centrum Nederland (Holland).

The design is described of a reactor of the type operated with the nuclear fuel in a granular state, the latter moving continuously in a closed circuit between reactor and heat exchanger(s). The mixture circulated may consist of individual grains of the fuel and moderator material or of composite grains. The mixture is fed into the reactor at the top, passes through the reactor under the action of gravity and is discharged at the bottom. It then enters a stream of helium or carbon dioxide gas and is conveyed by entrainment through the heat exchanger and back to the point of entry at the top of the reactor.

B.P. 800,636. Method and device for the sensing of neutrons. Siemens-Schuckertwerke A.G. (Germany).

A neutron detection device is described employing a semiconductor as the sensitive element. Detection is effected by recording the changes in the electrical characteristics of a semiconductor on exposure to neutrons. It is proposed to use materials comprising an element of the third group and an element of the fifth group of the Periodic System and to incorporate also at least one of the two elements boron and nitrogen. Nitrogen compounds are particularly suitable for the detection of neutrons of medium and large energy and boron compounds for the detection of slow neutrons.

B.P. 800,671. Fuel elements for nuclear reactors. H. M. Finniston and U.K. Atomic Energy Authority.

The element described consists of a settled slurry of finely divided fuel or a suspension of the same in liquid metal, contained in a double-walled (stainless steel) tube, the walls of the latter being some 1/16-1/10 in. apart. The carrier metal should have a melting point below the operational temperature of the reactor, i.e., below 600°C (or higher where applicable). Suitable metals are: lead, sodium and lithium. The proportion of fuel to metal should be of the order of 34:66 (in the case of suspensions, up to 40 : 60).

B.P. 800,730. Process for the enrichment of water in deuterium oxide. U.K. Atomic Energy Authority.

Details are given of the exchange reaction between water and deuterium-containing hydrogen in the presence of a catalyst of the type: nickel on a chromium sesquioxide base, platinum on alumina or on silica or carbon, and palladium on carbon.

B.P. 800,791. Separation of uranium from thorium. U.K. Atomic Energy Authority (U.S.A.).

On exposure of thorium to slow neutrons a (comparatively) small amount of uranium is formed in the irradiated material. From the irradiation product an aqueous solution is prepared of thorium and uranium nitrates, the proportion of nitrate:water ranging from 0.7 : 1 to 1.4 : 1 and the proportion of uranium:thorium not exceeding 1:50. This solution is treated with diethyl ether resulting in preferential extraction of the uranium.

B.P. 800,851. Dual temperature isotope exchange process. U.K. Atomic Energy Authority (U.S.A.).

A process for the concentration of deuterium in cyclohexane and hydrogen is described. Two interconnected exchange units are provided, one operating at 100°C and the other at 250°C. The hydrogen and cyclohexane gases are passed successively through the two units and intimate mixing is obtained by countercurrent action. The low-temperature unit promotes the transfer of deuterium from the hydrogen to the cyclohexane and the high-temperature unit promotes deuterium transfer in the reversed direction. The operational pressure in the units may be 100 atm.

B.P. 801,288. Fuel for nuclear reactors and process of making the same. B. M. Abraham and H. E. Flotow (U.S.A.).

Uranium or suitable uranium compounds such as the dioxide, nitride, silicide and carbide are suspended in liquid sodium heated above melting point or a sodium-potassium mixture. The fuel may represent 20% of the total volume; the fuel particles should not be larger than 5 microns, a size which can be obtained by grinding the material in a ball mill for 48 hours using toluene as lubricant.

B.P. 801,379. Recovery of plutonium. U.K. Atomic Energy Authority (U.S.A.).

If an aqueous solution of fission products, in which plutonium may be present, is brought into contact with diatomaceous earth, silicon gel or magnesium silicate, the plutonium will be adsorbed preferentially to uranium or other fission materials. The adsorbed plutonium may be eluted with 6N nitric acid.

B.P. 801,381. Production of uranium dioxide masses. P. Murray and U.K. Atomic Energy Authority.

Uranium dioxide masses of high bulk density are produced by sintering cold-pressed masses (preferably) of $UO_{2\cdot05}$ to $UO_{2\cdot15}$ in an inert atmosphere at 1200° to 1500°C or higher, for periods ranging from ½ hour to 2 hours.

B.P. 801,384. Scintillation screens. G. V. Planer, R. W. Windebank and G. V. Planer, Ltd.

The conventional type of scintillation screen has a cover of extremely thin aluminium foil to serve as a reflector. The fragility of this foil frequently causes failure. In the screen, designed according to the present invention, the phosphor particles are embedded in a (light-) transparent carrier of polystyrene or polymethyl methacrylate, the carrier being closer to the phosphor surface than in the past. The surface may be coated with one or more metallic layers by means of cathodic sputtering or vacuum evaporation, or alternatively by transfer methods.

B.P. 801,520. Separation of plutonium. U.K. Atomic Energy Authority (U.S.A.).

The separation of plutonium from fission products in aqueous solutions is effected by forming a water-insoluble complex of plutonium with cupferron. The complex is probably chelate. The method can be employed in an advanced phase of the process of isolating plutonium from neutron-irradiated uranium.

B.P. 801,521. Separation of uranium, plutonium and fission products. R. Spence and M. W. Lister (Canada).

A method of recovery from aqueous solutions is described which involves saturating the solution with a nitrate salt, reducing the plutonium to the tervalent state and extracting the neutral solution with a water-immiscible solvent for uranium. After the extraction of uranium the neutral aqueous solution is treated with an oxidizing agent, acidified with nitric acid, and subsequently the plutonium is extracted with a water-immiscible organic solvent for the oxidized plutonium.

B.P. 801,573. Recovery of thorium. A. Audsley, R. W. Blundell and U.K. Atomic Energy Authority.

Aqueous sulphuric acid solutions containing thorium and rare earth and phosphate can be obtained by heating monazite with concentrated sulphuric acid, diluting the cooled reaction product with water, and separating the insoluble residue from the supernatant thorium-containing solution. From the latter solution the thorium is recovered by introducing ammonium into the solution, increasing its pH value to a maximum of 0.6. As a result the rare earth is deposited in the form of ammonium rare earth double sulphates. The sulphates are then separated from the solution and the acidity is reduced (by adding ammonia solution) in order to precipitate thorium phosphate.